THESIS

A PALEOHYDROLOGIC INVESTIGATION IN THE VICINITY OF HARPERS FERRY, WEST VIRGINIA

Submitted by

Susan Jane Fuertsch

Earth Resources Department

In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 1992

QE
39.5
.P27
F83
1992
THESIS

Colorado State University

August 26, 1992

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY SUSAN JANE FUERTSCH ENTITLED A PALEOHYDROLOGIC INVESTIGATION IN THE VICINITY OF HARPERS FERRY, WEST VIRGINIA BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF EARTH RESOURCES.

Committee on Graduate Work

Ellen E. Wohl
Adviser

Department Head

COLORADO STATE UNIVERSITY LIBRARIES

ABSTRACT OF THESIS

A PALEOHYDROLOGIC INVESTIGATION

IN THE VICINITY OF

HARPERS FERRY, WEST VIRGINIA

A paleohydrologic investigation of the Shenandoah River in the vicinity of Harpers Ferry, West Virginia, was conducted in response to the recent periodic floods that devastate the community. The study reach was approximately 7.5 km long and consisted of thirty-two surveyed cross-sections.

Gaging stations established in 1895 at Millville, West Virginia and in 1882 at Harpers Ferry, West Virginia record flows ranging from a maximum of 6,509 m^3s^{-1}, to a minimum of 2 m^3s^{-1}. The average annual peak discharge for a seventy-year water record was 1,244 m^3s^{-1}.

Botanical flood evidence preserved as adventitious sprouts, tree scars and eccentric rings were documented in thirty-seven trees. A flood chronology established from these data extended from 1896 to 1955 after which no botanical indicators were found. Botanical indicators did not extend the systematic record, but they did provide an accurate, although not complete, flood chronology. The completeness of the botanical flood record is highly

Sedimentological flood evidence was limited within the study area due to the influence of a humid-temperate climatic regime, which is not conducive to the stratigraphic preservation of individual flood depositional units.

Human habitation of the area began in 1733; therefore, qualitative historical records were plentiful. Various historical records were cross-referenced to yield the most complete flood history. The correlation between the various sources was extremely high, demonstrating the comprehensiveness of the record. The historical flood record extends from 1748 to the beginning of the systematic record in 1896.

The ability to determine accurate flood stages from paleoflood indicators varied highly. Botanical indicators were found to yield very inaccurate and inconsistent flood stages, and only minimum values of flood stage could be obtained from these data. Historical data did yield accurate stages; however, these stages did not necessarily yield accurate discharge values, depending upon the stationarity and hydraulic complexity of the area.

Susan Fuertsch
Department of Earth Resources
Colorado State University
Fort Collins, CO 80523
Fall 1992

ACKNOWLEDGEMENTS

I gratefully acknowledge the financial support I have received from the National Park Service, the Hal Boyne Graduate Scholarship award, the Geological Society of America Research Grant, and the Sigma Xi Research Fund. I also wish to acknowledge the support and time given me by the Harpers Ferry National Historic Park employees with special thanks to the following: Mr. Harvey Sorenson, Mr. Bob Mackreth and his supportive boat crew, and Ms. Susan Frey for her extensive knowledge of the area and willingness to be my long-distance correspondent.

I also wish to thank my committee members including, Dr. Jose Salas, and Dr. John Stednick, with a special thanks to Dr. Ellen Wohl for her time, patience and expertise in the field of paleoflood reconstructions. I also wish to extend my gratitude to my field assistants, specifically my father, Mr. David Fuertsch; without their help the completion of the project would have been impossible.

Other sources of guidance were oriented towards specific aspects of my research. My botanical investigation would not have been complete without the humor and expertise of Dr. Tom Yanowsky, and Dr. Cliff Hupp. I also wish to thank all those who spent considerable time and energy advising my research efforts using the MAX model including; Dr. Jim O'Connor, Ms. Lisa Ely, Dr. Timothy Cohn, and a special thanks to Dr. Jerry Stedinger, Dr. Bob Webb, and Ms. Marian Fisher.

Finally, I wish to acknowledge Mr. Jeff Fanok for his constant smile, support, and understanding during this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

BACKGROUND AND OBJECTIVES

Introduction

The ability to predict the occurrence and magnitude of floods has grown increasingly important as human habitation and expansion continues toward flood-prone areas. The costs of structural damage and the loss of human lives in floodplain areas has created much controversy over the most accurate and precise method used to conduct flood frequency studies.

Conventional flood frequency analysis uses statistical procedures to estimate discharges with some specific probability of being exceeded. Systematic records are used to determine the flood frequency distribution, with the larger flood event being extrapolated from the smaller, more frequent events (Reed, 1990). Unfortunately, the period of record is often limited both spatially and temporally, thereby creating inherent inaccuracies in the extrapolation to the larger, more disastrous floods. The accurate prediction of the recurrence and magnitude of these larger events is necessary to insure the safe zoning of inhabited floodplain areas.

In response to the inaccuracies introduced by conventional flood frequency analysis, techniques have been developed which incorporate paleohydrologic flood data beyond those provided by systematic records. Paleohydrologic indicators extend the completeness of data coverage in time, space, and in scale (Baker, 1987), thereby increasing the accuracy of flood frequency analysis. This thesis illustrates some of the paleohydrologic techniques involved in paleoflood studies. As an example of the applicability of paleohydrologic techniques to flood frequency analyses, an analysis was conducted for the area in the vicinity of Harpers Ferry, West Virginia, a town devastated by numerous floods throughout its history (Janssen, 1985; Lee, 1988). It should be emphasized that the flood frequency analysis simply exemplifies an application of paleoflood studies and is not a major focus of this thesis.

Study Objectives

Harpers Ferry National Historic Park is presently attempting to restore Virginius Island, located along the left bank of the downstream reaches of the Shenandoah River. Historically, Virginius Island consisted of several human-made islands, each separated by canals used for transportation and power generation. In response to the devastating floods that periodically destroyed the community, the area was abandoned and the canals left to infill naturally. To effectively design mitigation and restoration strategies for future floods in this area, the National Historic Park has requested a paleohydrologic investigation of the area.

Specific objectives were:

1. to use historical, botanical, and sedimentological research to reconstruct the paleoflood record (the sedimentological research will involve a paleostage and channel stability investigation);

2. to conduct a channel stability investigation involving floodplain sediment, rebar and aerial photograph investigations;

3. to determine and analyze the accuracy of water surface profile estimates obtained from paleoflood stage indicators;

4. to determine discharge estimates from the paleoflood stage indicators; and

5. to use the above paleoflood data in a flood frequency analysis of the site.

Literature Review

Paleofloods are floods that occurred before the time of continuous systematic records or direct measurement of river discharges (Costa, 1984). Paleoflood reconstruction determines the paleoflood peak stage from both geomorphic and hydrologic techniques (Jarrett, 1989). The geomorphic approach determines the paleoflood peak discharge through regime-based reconstructions, which relate drainage network characteristics to the past flow conditions (Williams, 1988), and paleocompetence reconstructions, which relate the transport of channel sediments to flow properties (Costa, 1983; Williams, 1988; Komar 1988). These reconstructions determine the mean-flow velocity and cross-sectional channel area, which are then used to calculate the paleodischarge (Jarrett, 1989).

The hydrologic approach involves the use of paleostage indicators including historical, botanical (Hupp, 1988), and sedimentological evidence (Patton et al. 1979; Kochel and Baker, 1982; Baker et al. 1983; Ely and Baker, 1985; Partridge and Baker, 1987; Kochel and Baker, 1988; Webb and Rathburn, 1988). This approach will be the focus of this thesis.

Historical data can be obtained from many sources including written flood documentation, personal communication and the physical marking of observed flood stages. Flood marking is a common response to catastrophic floods (Stedinger and Cohn, 1987). A study of the Yangtze River documented finding numerous stone carvings and monuments with successive flood inscriptions dating from 1153 to 1870 (Chen et al., 1974).

Botanical indicators have been widely used to reconstruct discharge and other hydrologic variables (Fritts, 1976). These indicators include corrasion scars, adventitious sprouts, ring anomalies and tree age (Hupp, 1986, 1988). Corrasion scars and adventitious sprouts are easily recognized, and very valuable for paleoflood reconstruction. Both corrasion scars and adventitious sprouts result from large floods, which damage floodplain vegetation by creating outwardly evident stem or bark deformations (Sigafoos, 1964; Harrison and Reid, 1967; Yanosky, 1983, 1984; Hupp, 1988). The occurrence of numerous adventitious sprouts was documented in flood-damaged trees growing along the Potomac River, which were used to establish a flooding chronology for the site (Sigafoos, 1964).

Although ring anomalies and tree age are not outwardly evident flood indicators, they are very valuable for paleoflood reconstructions. Anomalous tree ring growth patterns (Yanosky, 1982a, 1983) have been used in numerous studies, specifically along the Potomac River (Yanosky 1983). Here it was found that many trees exhibited flood-induced ring abnormalities, which were used to supplement the flood record (Yanosky, 1983).

Tree ages aid in determining the date of deposition or erosion of various landform surfaces (Everitt, 1968; Costa, 1978). Tree age determination was very useful for surfaces scoured by the December 1964 floods in northern California (Helley and LeMarche, 1973). The age of the surface was estimated by determining the age of the damaged trees. These trees, having survived all previous floods in at least the last 200 years, indicate that a flood of this magnitude has not occurred for approximately 200 years.

Sedimentological evidence of paleofloods includes silt and scour lines, lichen boundaries, and debris and slackwater deposits. Slackwater deposits have become extremely valuable for paleoflood reconstructions.

Slackwater deposits selectively record the maximum flows, which are often missing from inadequate systematic records (Ely et al., 1991). The magnitude and frequency of past floods can be determined through dating and estimating the elevation of the sediments.

This technique was applied to slackwater deposits found in the mouths of tributaries that were backflooded during the catastrophic Missoula glacial outbreak floods (Bretz, 1929). Recent investigations of these deposits have estimated both the number and chronology of Pleistocene floods (Baker, 1978; Bunker, 1982; Waitt, 1980, 1984, 1985; Baker and Bunker, 1985).

Once the peak stages indicated by the various data (historical, botanical, and sedimentological indicators) have been determined, the respective paleoflood discharges can be estimated. Some of the earliest paleoflood estimates used the Chezy equation and erosional evidence to determine discharge estimates for the Missoula glacial outbreak floods (Bretz, 1925). Since this initial attempt, recent research has resulted in numerous methodologies to calculate the flood discharge associated with a particular flood stage.

Eventually, the slope-area method was developed for approximating peak discharge (Dalrymple and Benson, 1967). This technique is currently widely used despite yielding consistently high discharge estimates relative to actual measured values (Jarrett, 1984).

Presently, rating curves, the Manning's equation and numerous computer models are used to calculate discharge values. Rating curves, being dependent upon a specific channel geometry, are only applicable to flood stages which are in very close proximity to the gaging station. Otherwise, the Manning's equation or computer models must be applied. Step-backwater computer models yield the most accurate approximation for paleodischarges.

Numerous step-backwater models exist, including HEC-2, developed by the U.S. Army Corps of Engineers (Hydrologic Engineering Center, 1982), WSP2, developed by the Soil Conservation Service (Soil Conservation Service, 1976) and the U.S. Geological Survey's Step-Backwater Model E431 (Shearman, 1976; O'Connor and Webb, 1988). Selection of the hydraulic model is based upon channel characteristics and the type of flood-elevation data being used (Jarrett, 1989). Computed paleodischarges may then be used to conduct a flood frequency analysis for the area.

Historical records, and botanical and paleostage indicators frequently present a statistical sampling problem for flood frequency analysis. It is difficult to ascertain the exact flood discharge associated with this data set; therefore, one needs to be able to define a time period and a threshold discharge, Q_o, such that over that period all floods greater than Q_o leave a record (Stedinger and Cohn, 1986).

Current research in flood frequency analyses has documented the value of Maximum Likelihood Estimators (MLEs) for integrating historical and paleoflood information (Stedinger and Cohn, 1986). Maximum likelihood estimates function to determine the parameters of a distribution from which floods are assumed to come (Baker, 1989). MLEs achieve this by maximizing the probability of observed flood events. Researchers have developed MLEs for: (1) the log-Pearson type III distribution (Condie and Pilon, 1983); (2) a Bayesian analysis using systematic-records and historical information for a partial duration series using a Weibull peaks-over-threshold distribution (Bernier et al, 1986); and (3) an alternative to historically-weighted moments with historical information, when fitting the 3-parameter lognormal distribution (Condie and Lee, 1982). MLEs accommodate for the need to define threshold values over a period of time.

Although paleohydrologic techniques are most commonly applied to paleoflood studies, they can be applied to floods occurring during recorded history in watersheds that have no gaging records and are too remote for human record keeping (Patton, 1987). Paleohydrologic techniques enhance the systematic record, yielding a more complete and accurate representation of flood history.

CHAPTER II

SITE DESCRIPTION

Location

The study area is the Shenandoah River and surrounding floodplains, from its convergence with the Potomac River in the vicinity of Harpers Ferry National Historic Park, West Virginia to approximately 7.5 km. upstream, in the vicinity of Millville, West Virginia (Figures 1 and 2). The Shenandoah River is a major tributary of the Potomac River and drains 7,873 km^2. The river is bedrock-controlled at the downstream confluence area, but grades into an alluvial channel upstream. Floodplain vegetation is dominantly a second-growth deciduous forest, with dense underbrush. The majority of tree stands do not exceed 100 years old, due to previous anthropogenic uses of the area.

Channel Geometry

The Shenandoah River has a relatively consistent channel geometry until reaching the upstream islands and meander bends (Table 1).

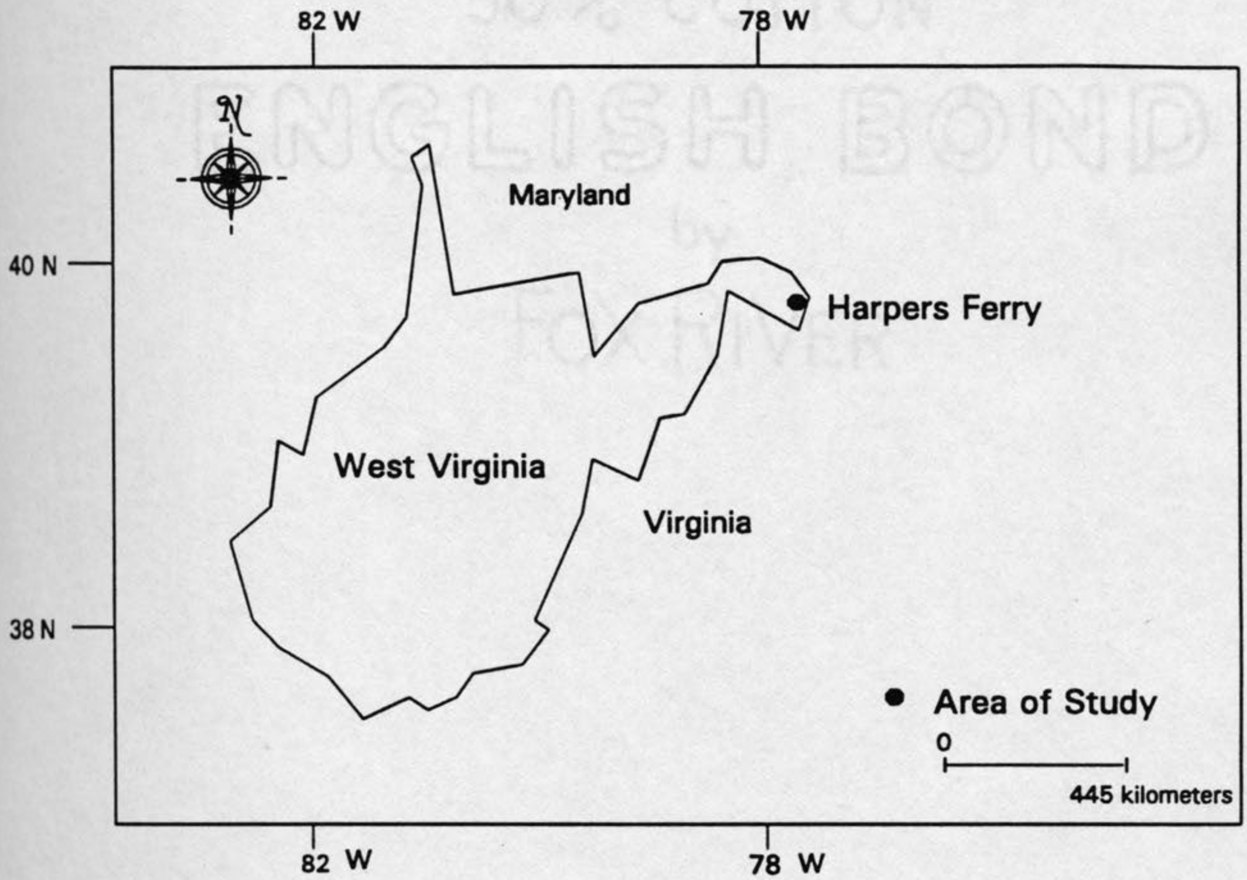


Figure 1. Geographic location of the study area.

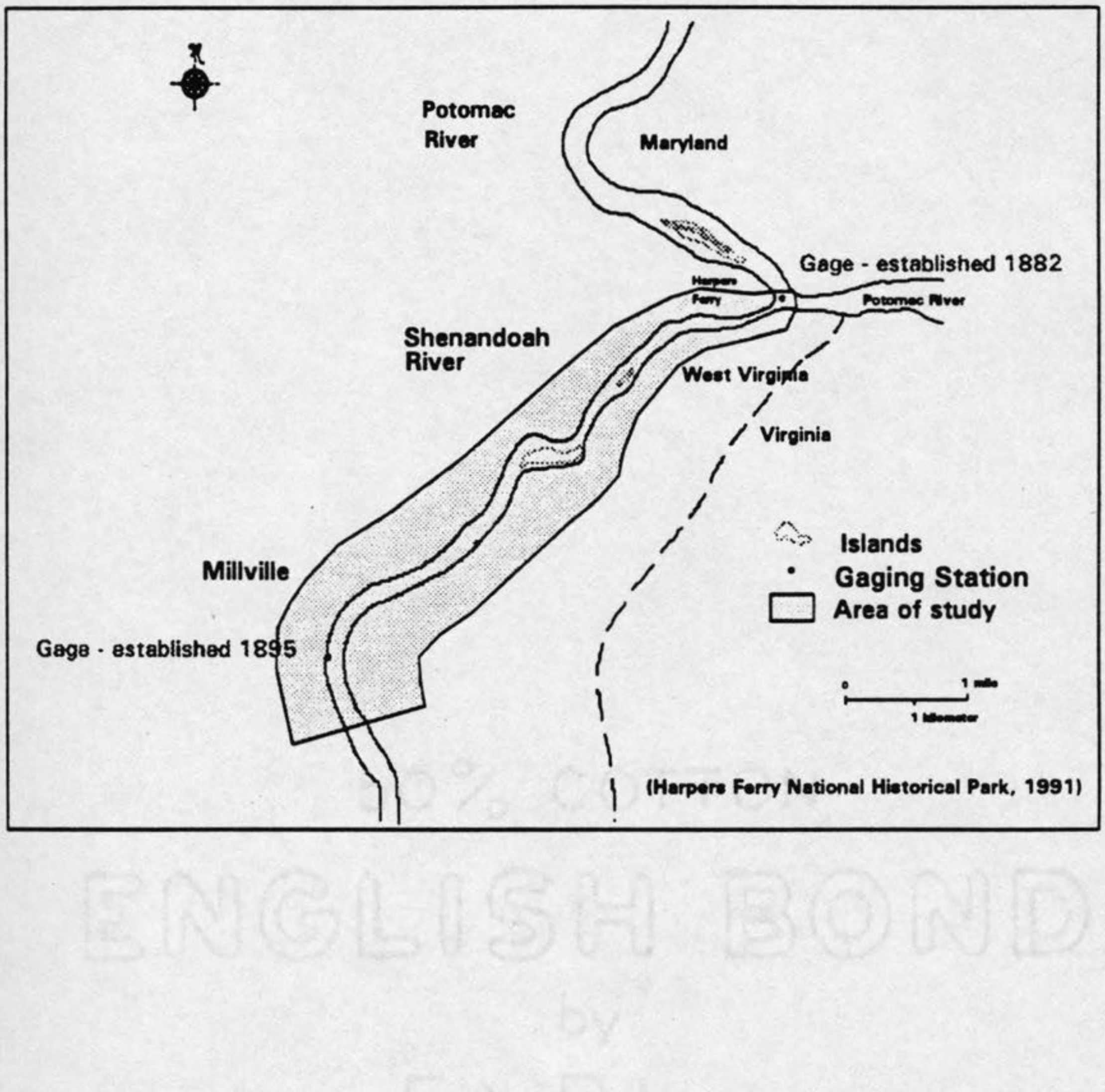


Figure 2. Specific location of study site. Gage locations are also shown.

Below the Rt.340 bridge, the Shenandoah River is a relatively shallow, straight channel, with bedrock outcrops and bedrock control exhibited specifically on the right bank (Figure 3). Upstream of this bridge, the channel becomes significantly more complicated, with numerous vegetated islands and backchannels. The channel configuration also becomes more complex and gradually shifts from a relatively straight to sinuous channel, consisting of several meander bends.

Table 1. Channel characteristics of the Shenandoah River within the study area.

Location	Max dpth	Width	Slope
x-2	1.21m	85.0m	.001
x-23	1.61m	119.0m	.018
x-30	1.17m	154.1m	.003
Location	**Average depth**	**Average Width**	**Average slope**
Avg. Channel	1.33m	119.4m	.007

Historical Background

Harpers Ferry National Historic Park was colonized by Peter Stephens, who operated the Shenandoah River ferry, in 1733. This ferry was taken over fourteen years later by Robert Harper, the town founder. Within a century after its settlement, the town had become a thriving industrial community (Gilbert, 1990). Water power supported the industry, and the navigability of the two rivers provided the needed transportation link between the east and west.

Industrial advances led to the navigational advances of the C&O Canal and the B&O Railroad.

The industrial prosperity and strategic location of Harpers Ferry resulted in the town oscillating between northern and southern control during the Civil War. The economy of the town plummeted as factories and bridges were annihilated.

Post-war efforts to rebuild the town failed due to floods in 1870, 1889, and the flood of 1936 (for a more complete historical chronology of Harpers Ferry see Table 2). The historical significance of the town during the Industrial and Civil War Era resulted in Harpers Ferry and the nearby vicinity being allocated as a National Monument in 1944 (Gilbert, 1990).

Geology

The Shenandoah River flows northeastward within the Appalachian Valley and Ridge, and Blue Ridge Physiographic Provinces of Virginia and West Virginia. It is underlain by Ordovician-age shales and sandstones in the south, while Cambrian-age limestones, dolomites and metamorphics dominate the underlying northern stratigraphy (Cardwell et al, 1968).

Table 2. Historical chronology for Harpers Ferry, West Virginia from 1733 to 1936 (Gilbert, 1990).

1733	Peter Stephens settles at "The Hole" where the Potomac and Shenandoah Rivers meet.
1748	Robert Harper purchases "The Hole" and operates the Potomac ferry.
1786	George Washington tours Harpers Ferry as a representative of the Patowmack Company.
1796	The U.S. Government purchases 118 acres for a federal armory and arsenal at Harpers Ferry.
1832	The C&O Canal is completed to Lock 33 across from Harpers Ferry.
1833	The B&O Railroad reaches the Maryland shore opposite Harpers Ferry.
1859	Abolitionist John Brown raids the U.S. Armory and Arsenal at Harpers Ferry.
1862	Stonewall Jackson surrounds and captures over 12,500 Union troops at Harpers Ferry.
1870	The Flood of 1870 takes 42 lives and destroys the town of Virginius.
1889	The Flood of 1889 ruins the last water-powered mill on Virginius Island.
1924	The Flood of 1924 closes the C&O Canal permanently.
1936	The record Flood of 1936 crests at 36.5 feet in Harpers Ferry.

Hydrology

The area of study contains two gaging stations; the Harpers Ferry gage, and the Millville gage (Figure 2). The Harpers Ferry gage, installed on the Chesapeake and Ohio Railroad bridge, is located on the Potomac River slightly upstream from the convergence of the Potomac and Shenandoah Rivers. The gage was established in 1882. Continuous records exist from November 1889 to present, with the exception of one record lapse from April to September, 1890.

The Millville gage, located immediately downstream of the town of Millville, West Virginia, was established in 1895 (Figure 2). Continuous records began in 1895 and extend until present, with the longest record lapse from March 1909 to August 1928 (Appendix 1).

The area of study is extremely vulnerable to flooding. Being in close proximity to the confluence of the Shenandoah and Potomac Rivers, the area has been subjected to three flood scenarios; the flooding of the Shenandoah River, the flooding of the Potomac River, and the simultaneous flooding of both rivers. Systematic flood records from the Shenandoah and Harpers Ferry gaging stations show that seven out of the ten largest floods occurred simultaneously, including; the 1924, 1936, 1937, 1942, 1955, 1972, and 1985 floods (Craig and Reed, 1990). The flood of record for the study area occurred in 1942, with an associated discharge of 6,509 m^3s^{-1}. The average annual peak discharge for the seventy-year water record is 1,244 m^3s^{-1}, with a minimum peak discharge of 154 m^3s^{-1}.

The Shenandoah River basin underwent significant changes in land-use practices, specifically during the Industrial Era, extending from the late 1700 to 1800's. Harpers Ferry and the surrounding vicinity are representative of these changes. The industrial boom began on Virginius Island between 1817 and 1824 (Janssen, 1985). A historical photograph collection illustrated the striking differences between Harpers Ferry during the Industrial Era, and Harpers Ferry during the late 1900's (Conway, 1981).

Historical photographs from the late 1800's were compared to recent photos of the same scene as they appear today. Photographs taken during the Industrial Era show the region denuded of vegetation and densely developed, whereas recent photographs of the identical scene show areas over-run with vegetation and buildings in ruin (Conway, 1981).

The Industrial Era led to the cutting of timber to sustain agricultural, fuel, and developmental demands. Roads and development increased soil compaction, resulting in increased runoff and sedimentation rates. Peak discharge lag times decreased, while flood discharges increased. The frequency of devastating floods during the 1800's did increase. It has been speculated that this occurred in response to the deforestation of the watershed (Janssen, 1985). Ultimately, channel adjustments occurred in response to the altered hydraulic regime. These changes continued after the Industrial Revolution.

The Post-Industrial Era was a time of environmental recovery throughout West Virginia, particularly in the Shenandoah and Cheat River basins (Kite and Linton, in press). Comparison of aerial photos taken in 1937, 1969, and 1991 illustrates the gradual recovery of the region during this time. The 1937 aerial photograph showed moderate revegetation of the area, but total recovery was not yet attained.

By contrast, the aerial photographs taken in 1969 and 1991, and a channel survey conducted in 1943, reveal that the area had restabilized by approximately 1940. The channel was surveyed in response to the emplacement of the Rt. 340 bridge, located approximately 1 km upstream of the Potomac and Shenandoah River confluence: Comparison of the 1943 channel survey with the survey conducted for this study demonstrates that this area of the channel has remained consistent from 1943 to the present.

If the probability distribution for the hydrologic regime remains constant through the period of record, the process and time series are considered stationary (Chow, 1964). The hydrologic regime during the Industrial and Post-Industrial Eras, extending from approximately 1800 to 1940, may not have remained constant; therefore, the flood records obtained during this period may not be representative of the current flood population due to non-stationarity.

CHAPTER III

METHODOLOGY

Before describing the methodology used specifically for this study, the general procedural outline used to conduct paleoflood studies will be described.

Description of General Procedures

Historical Evidence:

Investigating historic records involves researching various sources including: (1) physical anthropological evidence of flood stage (Figure 4); (2) published records and reports, including newspapers; (3) unpublished records and reports; and (4) information obtained from local residents. Generally, the accuracy of these sources decreases in the order listed (Thomas, pers. comm., 1992). The majority of these sources yield qualitative information, but through cross-referencing these data with measured stages of referenced points, quantitative stage estimates can be approximated. Caution should be exercised during stage estimation due to the inherent variability and inaccuracies introduced by human observation. To increase

Figure 4. Photograph of historical anthropologic flood evidence. Stage of the 1942 flood was chiselled into bedrock by flood spectator.

the reliability of these data, several reports of the same flood should be cross-referenced to determine the most precise stage estimate (Hupp, 1988).

Botanical Indicators:

There are four principal types of botanical evidence of floods, including; corrasion scars, adventitious sprouts, tree age, and ring anomalies (Hupp, 1986; 1988).

Corrasion scars are the most conspicuous and accurate forms of botanical flood indicators (Figures 5a and 6). They result from the impact of an object to the tree which locally destroys the cambium (wood-producing tissue). Growth in the area of impact temporarily ceases, thereby recording the date of damage. Eventually, the callus (undamaged tissue) begins to grow in annual increments over the scar (Hupp, 1988).

The scar may be physically evident for a number of years depending upon the growth rate of the tree, but eventually the outward expression of this scar diminishes. Scar height does not necessarily represent the maximum flood stage, but it can serve as an approximate indication (Harrison and Reid, 1967).

Adventitious sprouts grow from broken or tilted stems caused by floods (Bryan and Hupp, 1984) (Figure 5b, 5c, and 7). Sprouts usually begin to grow during the same season as the event or during the subsequent growing season.

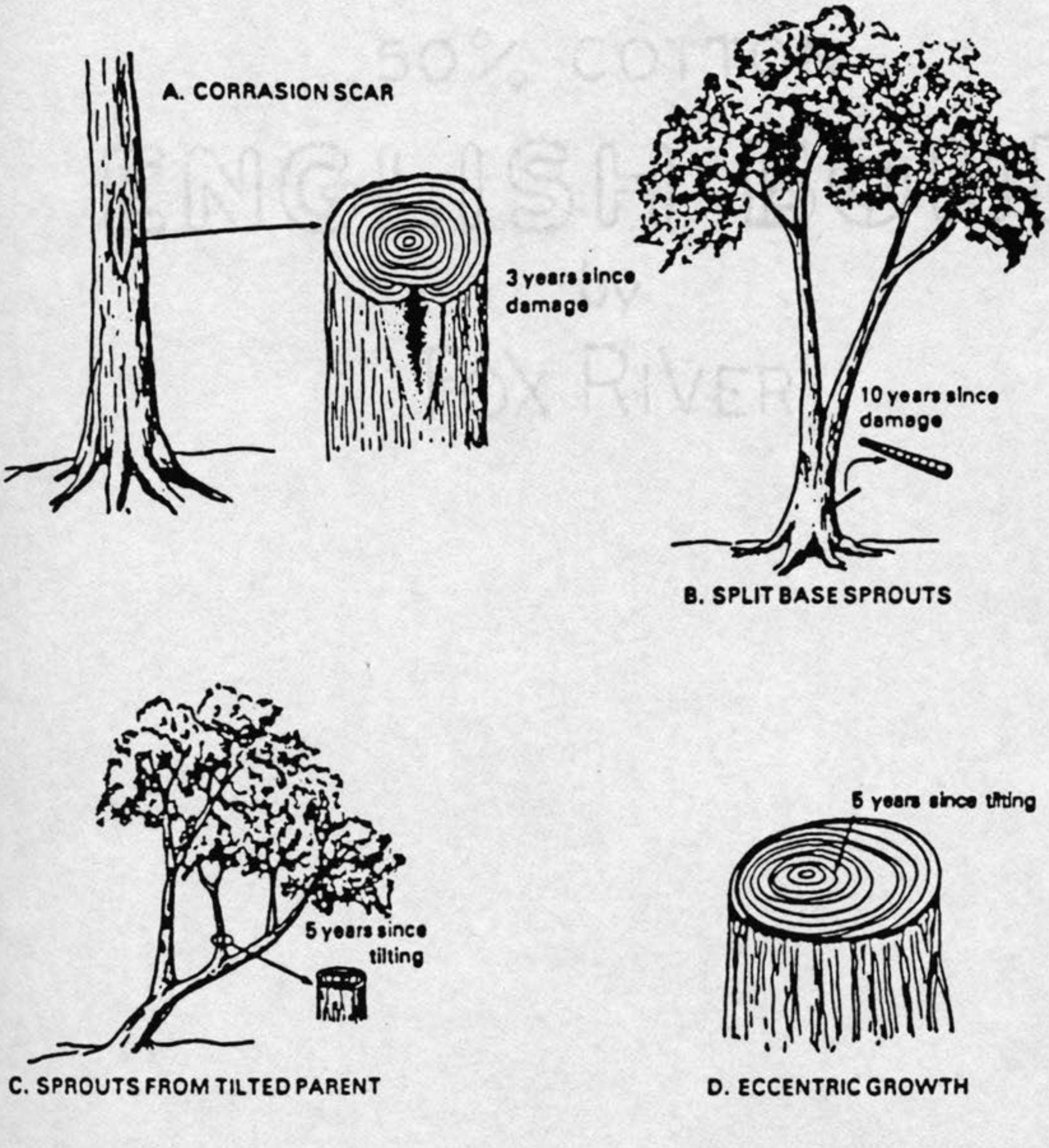


Figure 5. Types of botanical evidence of floods (after Hupp, 1988, Figure 10).

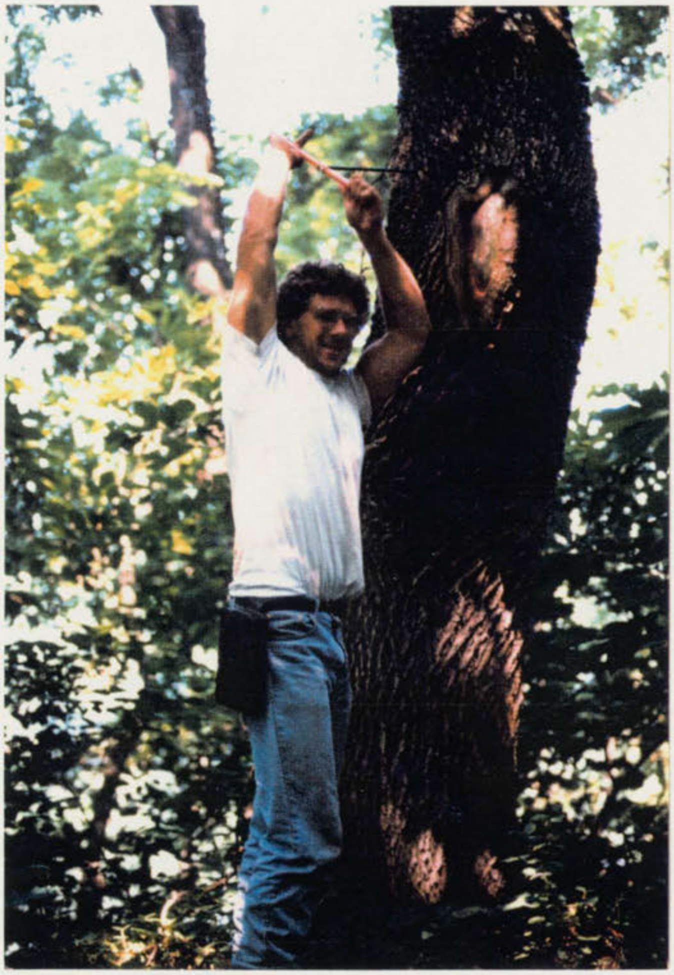


Figure 6. Photograph of typical corrasion scar.

Figure 7. Photograph of typical adventitious sprout.

Consequently, sprout age and the date of the flood event are nearly identical allowing for a year variation. Sprout age may be determined by coring to the center of the base of the sprout and cross-dating this age with sprout ages of other trees in the population (Cleaveland, 1980; Phipps, 1985). The term sprout is not necessarily used to indicate youth, as some sprouts exceed hundreds of years old (Hupp, 1988).

Two general types of adventitious sprouts occur; split-base sprouts (Figure 5b) and tilt sprouts (Figure 5c). Split-base sprouts form in response to a tree being truncated at its base, while tilt-sprouts are in response to a tree being inclined, usually in the downstream direction (Hupp, 1988).

Tree age can also be used for paleoflood reconstruction. Vegetation often becomes established on flood-scour or flood-deposited areas, within five years of the event (Helley and LaMarche, 1973). The majority of vegetation on this new surface will begin to grow at approximately the same time, producing a vegetative population very similar in age. The age of this stand approximates the minimum age of the surface (Everitt, 1968; Hupp, 1988).

Ring anomalies are abrupt changes in ring width (Yanosky, 1982b), or alterations in intra-ring anatomy (Yanosky, 1982a; 1983; 1984). They are formed in response to an event which alters either the orientation or growth potential of the tree, or both. Types of ring anomalies include eccentric ring patterns, suppression and release sequences and intra-ring abnormalities.

Slight tree tilts can cause eccentric ring patterns that are asymmetrical, with wider rings on the downstream side of the trunk, and narrower rings on the opposite side (Figure 5d). The date of the onset of this growth pattern is usually within one year of the event (Hupp, 1988).

Suppression and release sequences appear as abrupt changes in ring width, decreasing and increasing, respectively. Suppression sequences result from droughts, flood scour and damage, insect epidemics, fire, and overcrowding, whereas release sequences result from optimal environmental growth conditions including increased food resources and space availability. Due to the number of factors that could cause these sequences, this type of evidence may only be used as paleoflood data when it has been clearly established that the sequences are in response to a flood (Hupp, 1988).

Intra-ring abnormalities are zones of irregular tissue development within an annual growth increment. In the spring, tissue with large vessels (earlywood) is produced to facilitate the rapid transport of material upward to the budding leaves. As this rapid growth period begins to dwindle in the mid-to-late summer, the vessels become smaller (latewood) to accommodate for the diminishing demand of nutrients. This transition from large to small vessels is gradual. If within the latewood zone an anomalous earlywood zone suddenly appears, a flood may have inundated the tree, stripping it of its leaves. Increased nutrients are required to generate new leaves, and consequently large vessels are created.

The date of the annual increment within which this intra-ring abnormality occurs, determines the date of the flood. Flood stage may be estimated by approximating the height of the tree at the time of the flood (Yanosky, 1983).

Sedimentological Indicators:

Sedimentological indicators record the stage of individual floods by both erosional and depositional evidence. Often, they are in the form of silt and scour lines, lichen boundaries (Gregory, 1976), and debris and slackwater deposits. Silt and scour lines yield the most accurate stage estimate (Wohl and Enzel, in press), but slackwater deposits have been most widely used due to their ability to record both the peak minimum flood stage and the flood frequency through the absolute and relative dating of the deposits (Kochel and Baker, 1988).

Slackwater deposits are accumulations of relatively fine-grained sediments and organic matter deposited during episodes of high water. These deposits are located in areas of decreased velocity, which facilitates higher settling rates. Four geomorphic environments provide favorable conditions for the deposition and continued accumulation of slackwater sequences: (1) tributary mouths; (2) shallow caves or crevasses along bedrock walls; (3) high terraces; and (4) areas of abrupt channel widening and constriction (Kochel and Baker, 1988). Generally, bedrock channels with deep, narrow cross-sections provide optimal accuracy for this method (Wohl and Enzel, in press).

Paleostage estimates from slackwater deposits are determined by surveying the exact location and elevation of the deposits. To insure the accuracy of paleostage estimates, several qualifying assumptions must be accepted: (1) the flood deposits must be associated with the modern flow regime of the river; (2) channel cross-sections have remained relatively stable through time; (3) the channel has experienced no significant periods of aggradation or degradation; and (4) most importantly, the paleostage indicators must approximate the associated peak flood stage (Kochel and Baker, 1988).

Paleoflood Discharge Estimates:

Discharge estimates can be determined through the use of rating curves, the Manning's equation, and computer models. Rating curves determine the stage-discharge relationship associated with a specific channel geometry at a specific gage location. Therefore, if a flood stage is known in the vicinity of the gage, the discharge can be readily obtained from the rating curve, but rating curves will only produce accurate discharge estimates at that specific gage location.

The Manning's equation also facilitates discharge determination:

$$\text{Discharge} = n^{-1}\ A\ R^{2/3}\ S^{1/2}$$

where n is the Manning's roughness coefficient, A is the area, R is the hydraulic radius, and S is the frictional slope of the water-surface, with all variables in metric units. This equation yields an estimated or approximate discharge.

Various computer models determine water-surface profiles with their associated discharges. There are several variations between these computer models, but all are very similar in theory. The models use step-backwater techniques to generate computed water-surface profiles, based on the assumptions that flows are steady with time and gradually varied in space (O'Connor and Webb, 1988). In application, these assumptions imply that; the discharge in question affected the entire study area, the changes in flow characteristics between cross-sections are minimal, and the channel geometry remains constant over time (O'Connor and Webb, 1988). All models require a detailed survey of the study reach, which accurately characterizes channel geometry (Kochel and Baker, 1988), in order to precisely generate water-surface profiles.

Flood Frequency Analysis:

Maximum Likelihood Estimators (MLEs) allow for the utilization of both censored and binomial censored data in flood frequency analysis. Censored data record the magnitudes of peak floods, whereas binomial censored data record only threshold exceedance information (Stedinger and Cohn, 1986). By incorporating binomial censored data, historical and paleoflood data can significantly increase the accuracy of flood frequency analyses, through increasing the effective record length (Webb and Rathburn, 1988). Monte Carlo tests have shown that MLEs are more flexible, efficient, and robust than a historical flood adjusted-moment technique, suggested in Bulletin 17 (USWRC, 1982) when analyzing censored data (Stedinger and Cohn, 1986). Because of the uncertainties associated with discharge and stage estimates obtained from paleoflood studies, MLEs appear to be ideal for the integration of systematic and paleoflood data. MLEs can integrate flood frequency information provided by; systematic flood records, historical accounts, botanical evidence, and physical paleohydrologic information (Stedinger et al, 1988b).

Maximum likelihood techniques are utilized in the MAX computer program. MAX utilizes several probability distributions included in the normal/lognormal, Pearson/log-Pearson type 3, and Generalized Extreme Value families. MAX also determines the recurrence interval discharges for the 2-, 5-, 10-, 20-, 50-, 100-, 200-, 500-, and 1,000-year floods, in conjunction with their associated standard goodness of fit criteria of the observed versus the fitted values (Stedinger et al., 1988a).

Regardless of the type of model used to conduct the flood frequency analysis, flood frequency estimates are based on the assumption that the sample flood population is random and homogeneous, thereby exhibiting stationarity (Hazen, 1914).

In response to the extended time period covered by paleoflood records, the probability of these indicators occurring during changing environmental conditions or non-stationarity is increased; therefore justification of stationarity is essential to all paleoflood investigations (Webb and Rathburn, 1988).

Description of Study Methodology

Data collected for the Shenandoah River paleohydrologic reconstruction included a detailed survey of the study area, historical and botanical research, and a sedimentological investigation. These data, coupled with the available systematic flood records, enhanced the flood record used for the flood frequency analysis.

Channel Survey:

The channel survey characterized all channel irregularities, including constrictions, expansions, and changes in slope. The survey began at the downstream extreme of the study area on the left bank. Thirty-two cross-sections, including channel banks, geometry and flow indicators were measured using an electronic distance meter (EDM), rangefinder, and inclinometer. The EDM was the most accurate surveying instrument and measured to within 5 mm of the true distance. The rangefinder was less accurate but still measured to within 1-2 m of the true distance.

Cross-sections were surveyed perpendicular to flow direction, and spaced according to differences in channel characteristics (Figure 8). If channel width, depth, or flow characteristics varied, a cross-section was surveyed. Channel banks and geometry were surveyed independently to facilitate the finishing of one area before moving to another, but all were connected. Channel geometry was measured using the EDM, fathometer, and Zodiac motor boat. The fathometer, attached to the rear of the Zodiac motor boat, measured channel depth at a predetermined point, while the EDM measured the distance to that point.

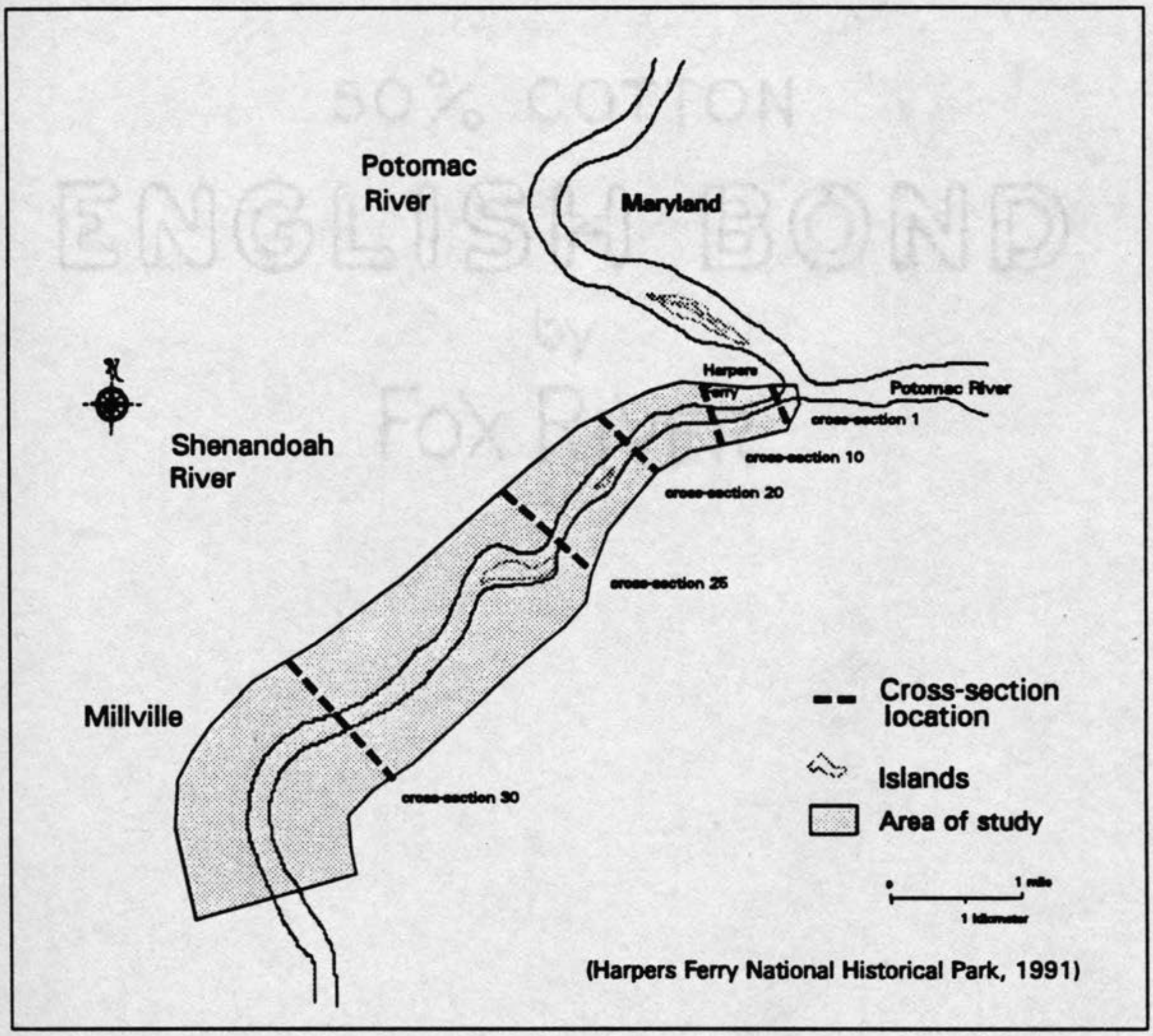


Figure 8. Selected cross-section locations within the study area.

Historical Research:

Various sources were explored for information pertinent to extending the quantitative flood record, including the B&O Railroad and C&O Canal annual reports, personal diaries and journals of flood victims, newspaper articles during the time period, church and business records and accounts of flood damage, and the Harpers Ferry National Historic Library. Additional information was gathered from personal communication with park service employees, and local residents (Figure 9). These sources were cross-referenced to determine the historic flood chronology and associated stages.

Botanical Research:

Field work for botanical evidence entailed traversing the floodplain area to locate any tree bearing potential flood evidence. Thirty-seven trees were marked, cored to their biological center (Figure 10), and noted. The base of each cored tree was located relative to the channel survey through the use of a range finder and inclinometer. Through this procedure, the cored trees were located spatially, both in elevation and distance along the channel. The tree core samples were stored in paper straws, to facilitate drying and safe storage, and transported back to the lab for analysis. Lab analysis involved core preparation. The cores were allowed to dry fully, then were mounted, sanded,

Figure 9. Photograph of various flood-stages recorded by Mr. Bob Allen, an inhabitant of the Potomac River floodplain.

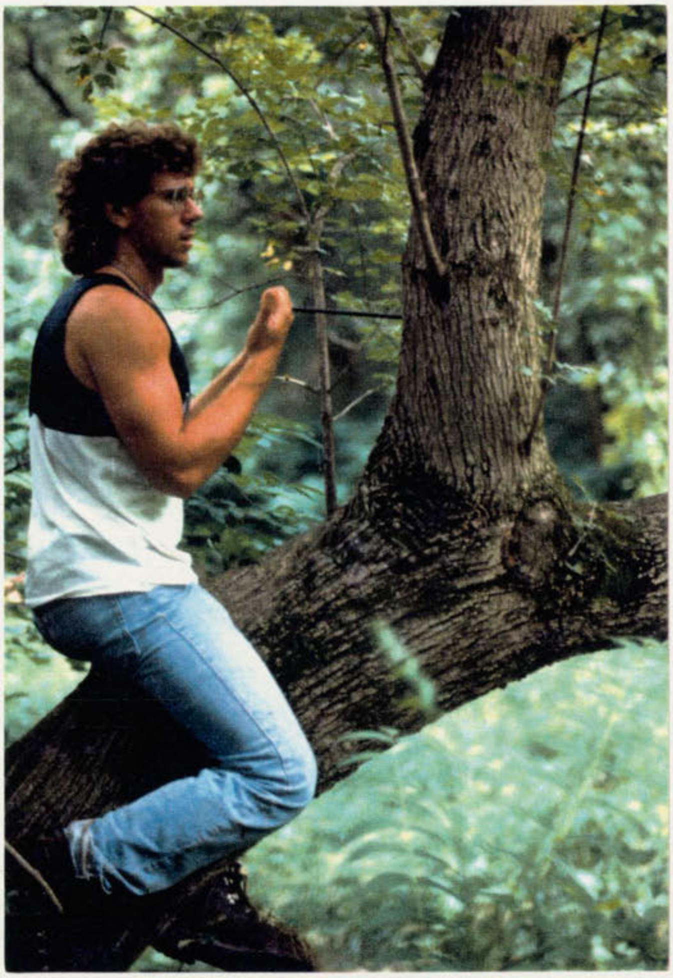


Figure 10. Photograph of coring procedure.

and microscopically examined using a binocular microscope (Figure 11). Analysis included determining core age, and identifying intra-ring abnormalities and suppression and release sequences. Possible flood dates were then tabulated and referenced back to their initial tree locations to determine the probable minimum flood stage associated with the tree damage. Botanical flood dates were cross-referenced with systematic records to calibrate the botanical stage information.

Sedimentological Research:

Sedimentological research involved both a paleostage and channel stability investigation. The paleostage investigation was performed in conjunction with both the channel survey and botanical research. Lichen boundaries, silt and scour lines, and debris and slackwater deposits were searched for and investigated. The type of evidence was noted and its location and stage relative to the channel survey was established. Investigating slackwater deposits required exposing fresh sedimentological surfaces. This entailed the manual digging of pits into the deposit. A stratigraphic analysis was conducted and datable material was collected. The datable material was stored in plastic ziplock bags to ensure containment during the transport from the field to the lab. The material was sorted, then sent to BETA Analytical Laboratory, where the material was analyzed.

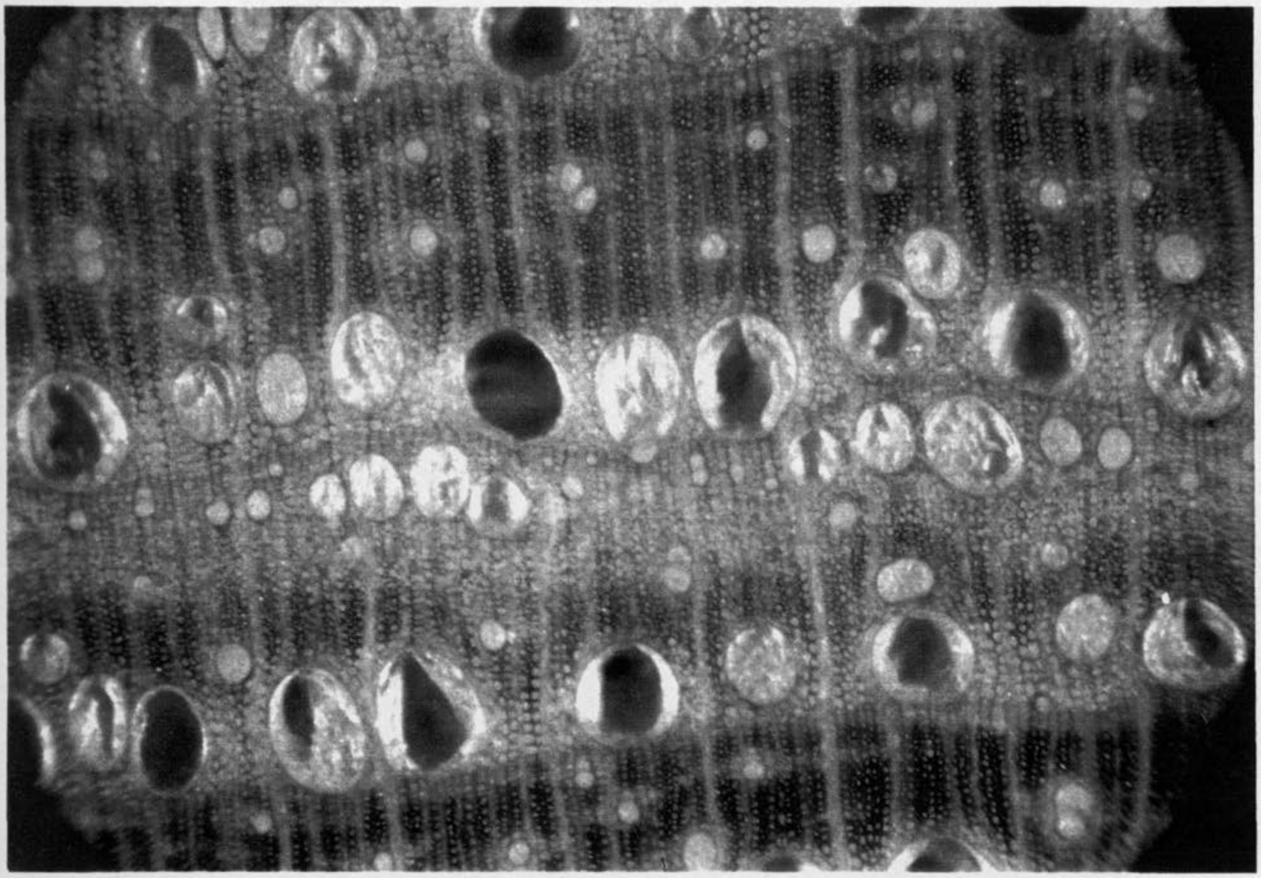


Figure 11. Photograph of microscopic analysis of tree core (after Yanosky, 1983).

The slackwater investigation contributed to both the paleostage and channel stability investigation by determining both the stage and sedimentation rate of the flood deposits.

Channel stability, particularly the rate of sedimentation, was also investigated by measuring the depth of burial or amount of exposure of numerous rebars originally emplaced flush with the ground surface on Virginius Island in 1979 during a magnetometer study. These rebars were set at fifty-feet intervals along a grid having a baseline along the centerline of the Baltimore and Ohio Railroad-Winchester line Right-of-Way. An exposed rebar, located through personal communication with J. Ravenhorst, 1991, was used as a starting point for finding the other rebars. From this rebar, fifty feet was measured along a line parallel or perpendicular to the baseline to locate the adjacent rebars. If an exposed rebar was located, the amount of exposure was measured and noted: If no rebar was exposed at this point, it was assumed to be buried. To determine the depth of burial, a pit was excavated until the rebar was found or until a pit the size of 100 x 100 x 150 cm was reached. If a rebar was found, the depth to burial was measured and noted. If no rebar was located, the site was noted and the search for other rebars commenced. Supposably, the rebars were not emplaced on any points occupied by a tree, asphalt, masonry, rock, or water.

The final component of the channel stability investigation involved the comparison of three aerial photographs from 1937, 1969, and 1991 to determine the rates of sedimentation on a larger spatial scale as well as to assess the amount and rate of channel change and adjustment that has occurred during the last 54 years.

Discharge Estimation:

Assuming steady-state, sub-critical flow that was gradually varied in space, HEC-2 was calibrated with the surveyed channel geometry by using the systematic records obtained from the Harpers Ferry and Millville gages. HEC-2 models the hydraulic characteristics of flow by using step-backwater techniques; therefore, flood stages and discharges were input for the downstream end of the study area, or cross-section #1. Through iterative step-backwater techniques, HEC-2 generates a computed water-surface profile. The accuracy of this computed water-surface profile was validated by comparing the flood stage measured at the upstream gage with the flood stage calculated by HEC-2. This procedure was repeated after necessary channel adjustments were made until the two water stages were identical.

After calibration of HEC-2, water-surface profiles were constructed for numerous floods occurring during the systematic record, which were documented by botanical indicators. This allowed for the comparison of the botanical flood stage estimates with the systematic flood stage.

Historical records cited flood stages at Harpers Ferry, West Virginia, in close proximity to cross-section #1 of the channel survey (Figure 8). As previously stated, if discharge estimates are to be determined for the stage estimates at cross-section #1, HEC-2 requires the initiation of the step-backwater program downstream of that cross-section. Immediately downstream of this cross-section, is the convergence between the Potomac and Shenandoah Rivers. This convergence area creates a hydrologically complex situation which HEC-2 cannot model. Therefore HEC-2 was not employed to determine the historical record's discharges. Instead, the Manning's equation and a rating curve were used to determine discharge values for the historical data.

The Manning's equation was only used to determine the range of discharges for the historical period of record, thereby determining only the minimum and maximum discharges. This was done as a comparison to the rating curve estimates and was also needed for the flood frequency analysis of the area. As previously stated, computing discharges from the Manning's equation requires the initial determination of several variables, including flood channel width, average flood channel depth, slope and the Manning's roughness coefficient. Flood channel width was determined by graphically reconstructing the channel geometry at cross-section #1 and then superimposing the various flood-water stages on the channel configuration (Appendix 2). Water depth was determined at ten points along the flood channel width and then averaged. Average channel slope and roughness coefficients, as determined in the field, are 0.001 and 0.038, respectively.

No rating curve was available for the Shenandoah River in the vicinity of Harpers Ferry. Consequently, a rating curve was constructed from the stage-discharge relationship determined from the systematic record (Chow et al, 1982), which was obtained from the both the Harpers Ferry and Millville gages. The Harpers Ferry gage established the Shenandoah River stage values at Harpers Ferry, whereas the Millville gage established the associated upstream Shenandoah River discharges. From this relationship, a curve was generated which was used to determine discharges associated with various stages.

To determine the best-fit rating curve used to estimate discharge values, three different curves were constructed and compared. The initial curve was representative of the pristine data, while the latter two graphs illustrate the rating curve after the data were transformed into a log-normal and log-log distributions (Appendix 3). The rating curves generated from the transformed data did not yield a more accurate or more normal distribution than the curve generated from the original data; therefore, discharge values were obtained from the initial curve which used the non-transformed data.

A regression analysis of the curve showed an R^2 value of 0.73 with the standard error of the y-estimate for discharge values being 778 m^3s^{-1} for a mean annual discharge of 2,462 m^3s^{-1} .

Flood Frequency Analysis:

The computer model MAX, (Stedinger, Surani and Therivel, 1988a), was used to perform the flood frequency analysis. Three flood frequency analyses were conducted. The first analysis was performed for the entire flood record, from 1748 to the present, while the second and third were conducted independently for the paleoflood and systematic records, respectively. A lognormal frequency distribution was used for ease of comparison.

Initial inputs for the program include tabulated flood dates with corresponding probable discharges or range of discharges, the period of record for the botanical, historical, and paleostage data, and threshold-discharge information. Threshold levels were determined for all analyses conducted and were based upon the flood stage required for a flood to be recorded by botanical and historical sources. Typically, thresholds will decrease with time because more is known about relatively recent flood stages (Stedinger et al., 1988a).

When the analysis was conducted for the entire period of record, two thresholds were used; a lower threshold which indicates a relatively recent flood level associated with flood stage (5.48 m) at Harpers Ferry, and an upper threshold (7.20 m), which during the early stages of colonization was the level that had to be exceeded for a flood to be noteworthy. The disparity in thresholds probably resulted from the increased development and habitation of flood-prone areas.

During the early colonization period, Harpers Ferry was sparsely inhabited. Space was abundant, and safe refuge from floods was plentiful by simply moving to higher ground. Usually the floods that are noted are those that damage property or endanger human lives. Due to the majority of the population being able to reside in safer areas, smaller floods did not pose a large threat, therefore only extreme events were recorded. As the population increased during the latter 1800's, the poor began to inhabit the floodplains, and much smaller floods were required to bring catastrophic ruin to the community. In response, the flood threshold decreased, and small as well as large floods were recorded much more diligently. Additionally, it was during this time that both the Harpers Ferry and Millville gages were established, which obviously decreases the flood threshold by recording daily flows in addition to floods.

The discharge value associated with the first and upper threshold was 80% of the 1748 flood discharge (2,340 m^3s^{-1}) (Cohn, pers. comm., 1992), whereas the second threshold's discharge was the value associated with flood stage (5.48 m) in Harpers Ferry (1,150 m^3s^{-1}) (Appendix 4). Only one threshold was used for the paleoflood data analysis and it was the same as the upper threshold (2,340 m^3s^{-1}) used during the analysis of the entire period of record. An arbitrary threshold of 6,500 m^3s^{-1} was used for the flood frequency analysis of the systematic data. This value was arbitrary because no threshold is actually needed for the systematic data, but, to operate within the framework of the model, a threshold must be specified.

CHAPTER IV

RESULTS & DISCUSSION

The total length of the flood record was 244 years. The systematic record extended from the present to 1896, while the historic record extended from 1893 to 1748. During the historical period, 57 floods were documented from historic, paleobotanic, and paleostage indicators.

Historical Records

Written historic records were abundant due to the early colonization of the area, and the political significance of the town. These data extended the systematic record from 1893 to the flood of 1748 (Table 3). Approximately 85% of the historical information was obtained from documented sources including the C&O Canal Annual and damage reports, newspapers, letters, books, and reports written by the National Historic Park. The most valuable of these sources was a flood chronology compiled in a park report (Larrabee, 1961).

With the exception of this report, the information obtained from these sources was qualitative. For example, the flood stage was said to be knee-high on Shenandoah Street, or to have caused damage to various canal locks and

Table 3. Historical flood chronology for Harpers Ferry, West Virginia, from 1748 to 1893.

Date of Flood	Year of Flood	Dominant River
unknown	1748	Both
unknown	1753	Shenandoah
unknown	1771	Both
unknown	1810	Both
unknown	1823	Potomac
unknown	1832	Potomac
unknown	1840	Potomac
April	1843	Both
Sept. 14	1843	Both
Sept. 21	1843	Both
Nov. 5	1846	Shenandoah
October	1847	Potomac
November	1847	Shenandoah
Apr. 18	1852	Both
Sept. 20	1859	Both
Nov. 8	1860	Both
April	1861	Both
Aug. 19	1861	unknown
Sept. 29	1861	Shenandoah
Mar. 9-10	1862	unknown
Apr. 9	1862	unknown
Apr. 13-14	1862	unknown
Apr. 22-23	1862	unknown
June 2-5	1862	unknown
Feb. 9	1863	unknown
Mar. 10	1863	unknown
Apr. 16-17	1863	unknown
May 6-8	1863	Potomac
Dec. 19-20	1863	Potomac
May 15-21	1864	Potomac
Feb. 27-Mar. 4	1865	Potomac
Mar. 17-18	1865	Both
May 12-13	1865	Potomac
May 21-24	1865	Potomac

Table 3. (continued)

Date of Flood	Year of Flood	Dominant River
Sept. 30	1870	Shenandoah
November	1877	unknown
unknown	1885	unknown
unknown	1886	unknown
unknown	1887	unknown
unknown	1889	Both
unknown	1891	unknown
unknown	1893	unknown

dams. If the canal was damaged, flow was assumed to overtop the canal (although damage could have been from lateral erosion). Knee-height on Shenandoah Street was derived by adding the average knee-height of a 5′ 8" man to the elevation of Shenandoah Street at approximately the mid-section of town.

The remaining information was obtained from a flood mark, which documented the flood of October 16, 1942 (Figure 4 and Table 4), and through personal interviews with local residents.

In addition to the historical record, floods were documented during the periods of record lapse for the Harpers Ferry and Millville gages extending intermittently from 1897 to 1928 (Figure 9). These floods were documented by the Harpers Ferry National Historic Library.

Botanical Indicators

Thirty-seven trees were cored, including species of sycamore (*Platanus occidentalis* L.), silver maple (*Acer saccharinum* L.), royal paulownia (*Paulownia tomentosa*), box elder (*Acer negundo* L.), basswood (*Tilia americana* L.), and ash (*Fraxinus americana* L.). The value of each species for tree ring analysis varied, ranging from ash as the best indicators to sycamores as the worst indicators. Tree species can be defined as ring or diffuse porous. Ring porous species have very clear, definitive ring boundaries, whereas diffuse porous species have nearly

Table 4. Flood dates from botanical and physical anthropologic evidence, and type of botanical evidence on the Shenandoah River, West Virginia.

Date	Adventitious Sprouts	Ring Anomalies	Historical Markers
1896	■		
1942	■		■
1949	■	■	
1955	■	■	

unidentifiable ring structures. Ash (a ring porous species) were found to be the most useful due to the clarity of its ring structures, whereas sycamore (a diffuse porous species) were almost useless due to their lack of ring clarity. Unfortunately, the majority of trees showing flood damage were sycamores. The sycamores' high incidence of flood damage was probably in response to their establishment in close proximity to the channel. Also, sycamore cores were frequently rotten towards the center of the core. This was very common in the older sycamores, and led to severe problems in dating the core.

The majority of flood-damaged trees were located in areas of the channel that were constricted and that exhibited some bedrock control, as seen in cross-sections #1 through #25 on the right bank of the Shenandoah River (Figure 12). In these areas, flood stage would be elevated and velocities increased, thereby facilitating the creation of botanical flood indicators. These areas are also conducive to the accumulation of woody debris, which serves to damage trees through impact. The outside of meander bends are also conducive to the creation of botanical indicators. Again, in these areas flow is elevated, leading to the increased likelihood of botanical flood damage.

Botanical indicators were found as close as 0.33 m from the channel to as far as 30 m from the channel. Obviously, indicator occurrence decreased as distance from the channel

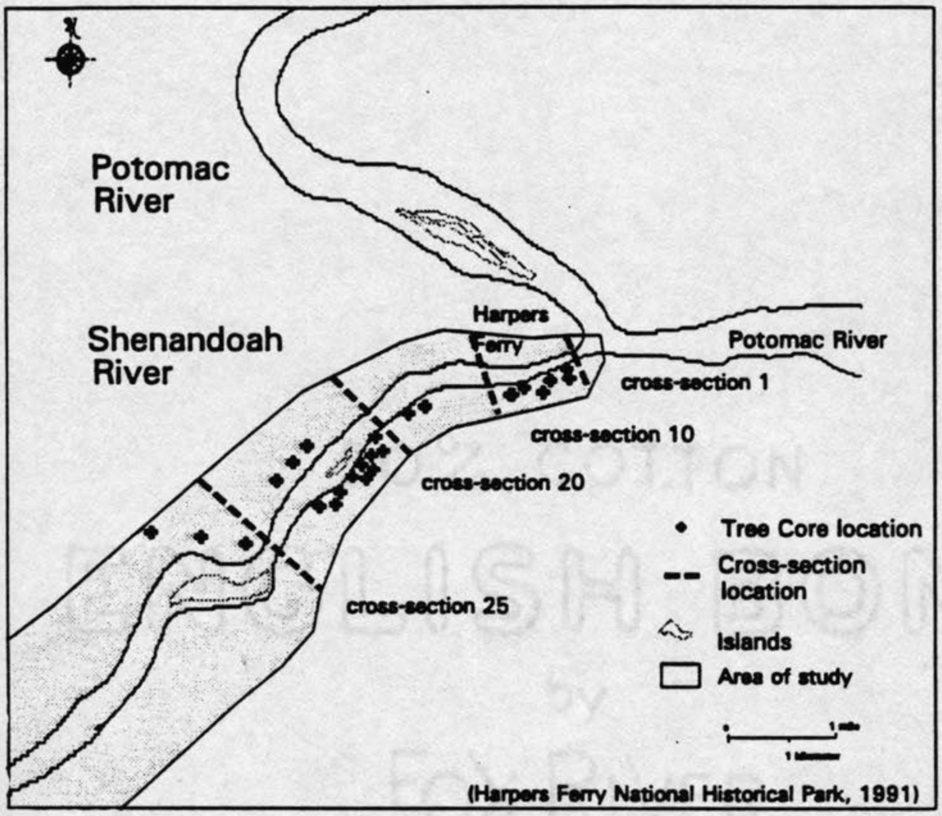


Figure 12. Tree core locations within the study area.

increased. Trees that are farther from the channel are less likely to receive flood-induced damage due to only being in potential flood danger during high-magnitude events which occur infrequently. Additionally, during these events the brunt of the flood force will be felt in the low-lying floodplain areas. Progressing away from the channel, unit stream power decreases, resulting in decreased flow velocities and decreased frequency and force of impacts from flood debris. Ultimately, these factors lead to the decreased occurrence of botanical indicators at increased distances from the channel.

Paleobotanical indicators, including corrasion scars, adventitious sprouts, and ring anomalies were found. Before any botanical evidence was incorporated into the flood frequency analysis, the flood had to be indicated by several high-quality specimens, specifically tilt sprouts and corrasion scars, which indicated a flood for a particular date (Hupp, 1988).

These indicators did not extend beyond the systematic period of record, with the oldest botanical indicator yielding a flood date of 1896. Other floods documented by botanical evidence were the floods of 1942, 1949, and 1955 (Table 4 and Figure 13). These flood dates, established from paleobotanic evidence, were then correlated with the systematic flood record. Although the botanical flood

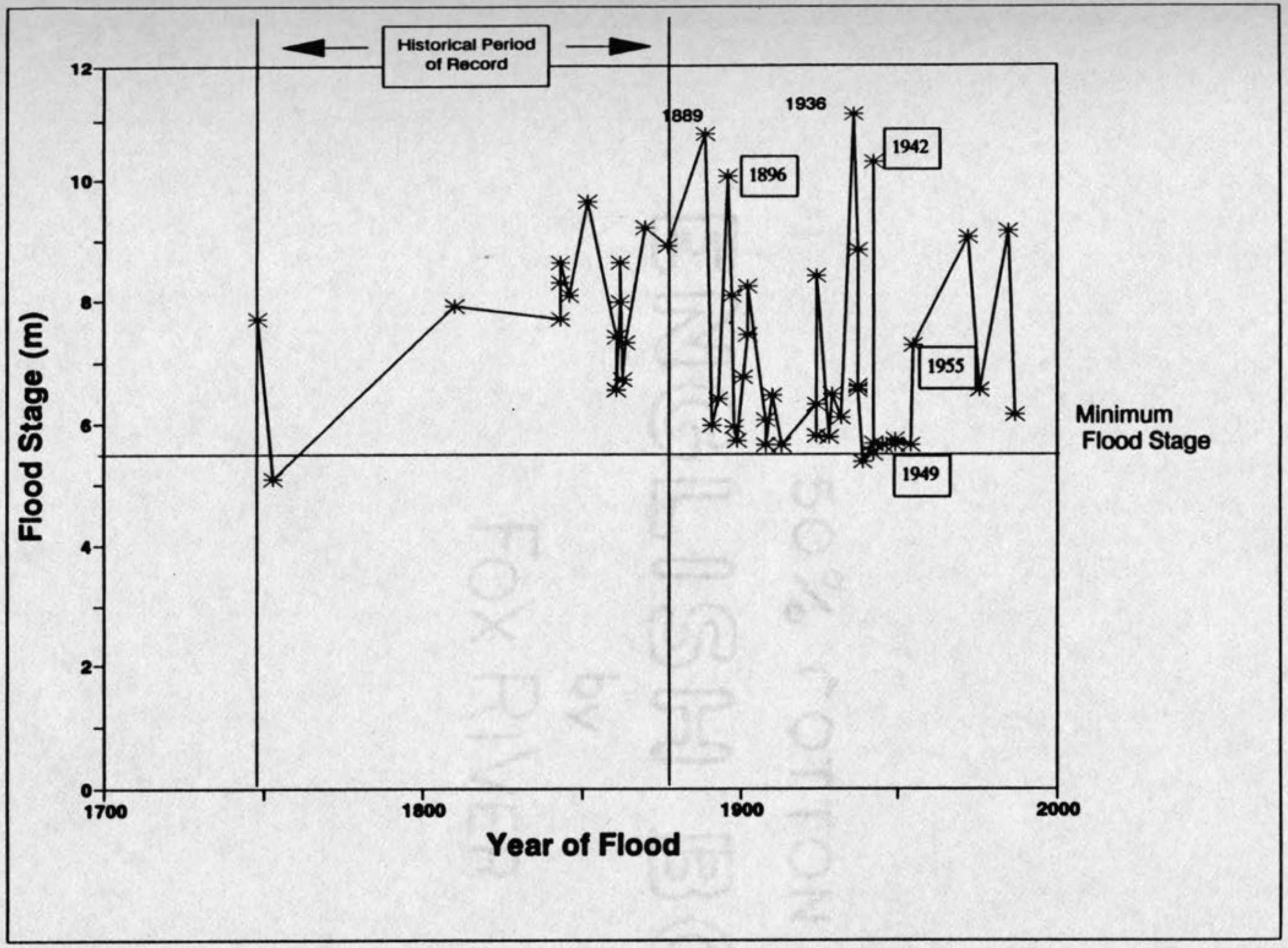


Figure 13. Flood stages for the total length of record for the Shenandoah River. Boxed dates indicate flood dates established from botanical and systematic evidence. Floods prior to 1877 are not supported by gage records. The stages of the botanical and physical anthropological data are not included due to the inaccuracies in stage estimates.

record did not yield as complete a flood chronology as the systematic records, all botanical flood dates were documented by the systematic record.

Sedimentological Indicators

Paleostage indicators were very sparse. Only minor amounts of flood debris were found and slackwater deposits were limited; however a flood deposit investigation was conducted on Virginius Island. The investigation, although not a slackwater analysis because the sediments investigated recorded relatively minor flood events, did yield insight into the stability of the area.

A total of five pits were dug and investigated (Table 5), but only three yielded datable material (Figure 14). Deposit ages ranged from 430 to 3,280 years BP. The validity of these dates is highly questionable.

Sites #1 and #5, yielded dates of 3,280 and 3,000 years BP, respectively (Table 5). Virginius Island was a highly industrialized community during the 1800's. Dissection of the original landmass by canals led to a series of interconnected manmade islands comprised of numerous mills and factories. Construction to this extent would significantly alter any flood deposit stratigraphy, particularly on Virginius Island where the soils are relatively shallow as illustrated by the exposed bedrock in the channel and on the island itself. Due to the pits'

Table 5. Sediment pit descriptions.

Site Number	Location	Description	Number of depositional units	Radiocarbon Ages[1]	Other PSI
Site 1	Approximately 27 m downstream of headgates and approximately 17 m from Shenandoah left bank	Shenandoah left bank floodplain, pit consists of poorly sorted mixture of sands, and sub-rounded gravel, and cobbles ranging in size from 1 to 18 cm along long-axis, Pit depth = 32 cm	1	None	In pit found bark, shell, and broken ceramic pieces
Site 2	Downstream of headgates, approximately 12 m north of Site 1, at bottom of railroad berm	Sand to sandy silt; dark lenses throughout consisting of black pebbles and organics Pit depth = 92 cm	3	430 ± 70 BP(B-51441)	Plastic tile found in 2nd layer
Site 3	Approximately 10 m upstream of Site 1 and approximately 18 m from Shenandoah left bank	Shenandoah left bank floodplain, pit consists of mostly sands, with intermixed gravel and sub-rounded cobbles, Pit depth = 74 cm	3	3,280 ± 130 BP(B-51440)	
Site 4	Approximately 10 m southeast of Trail Post #21	Shenandoah left bank terrace deposit with well established vegetation, silty to coarse sand Pit depth = 86 cm	4	None	At pit bottom found brick, slag, glass
Site 5	Immediately upstream of small island on Shenandoah left bank	High floodplain deposit consisting of coarse to silty sand, with fine grained organic lenses Pit depth = 1.7 m	5	3,000 ± 90 BP(B-51443)	Flood scars on island trees

[1]Radiocarbon ages are presented as years before 1950 AD (BP). Radiocarbon laboratory is B-Beta Analytic Inc..

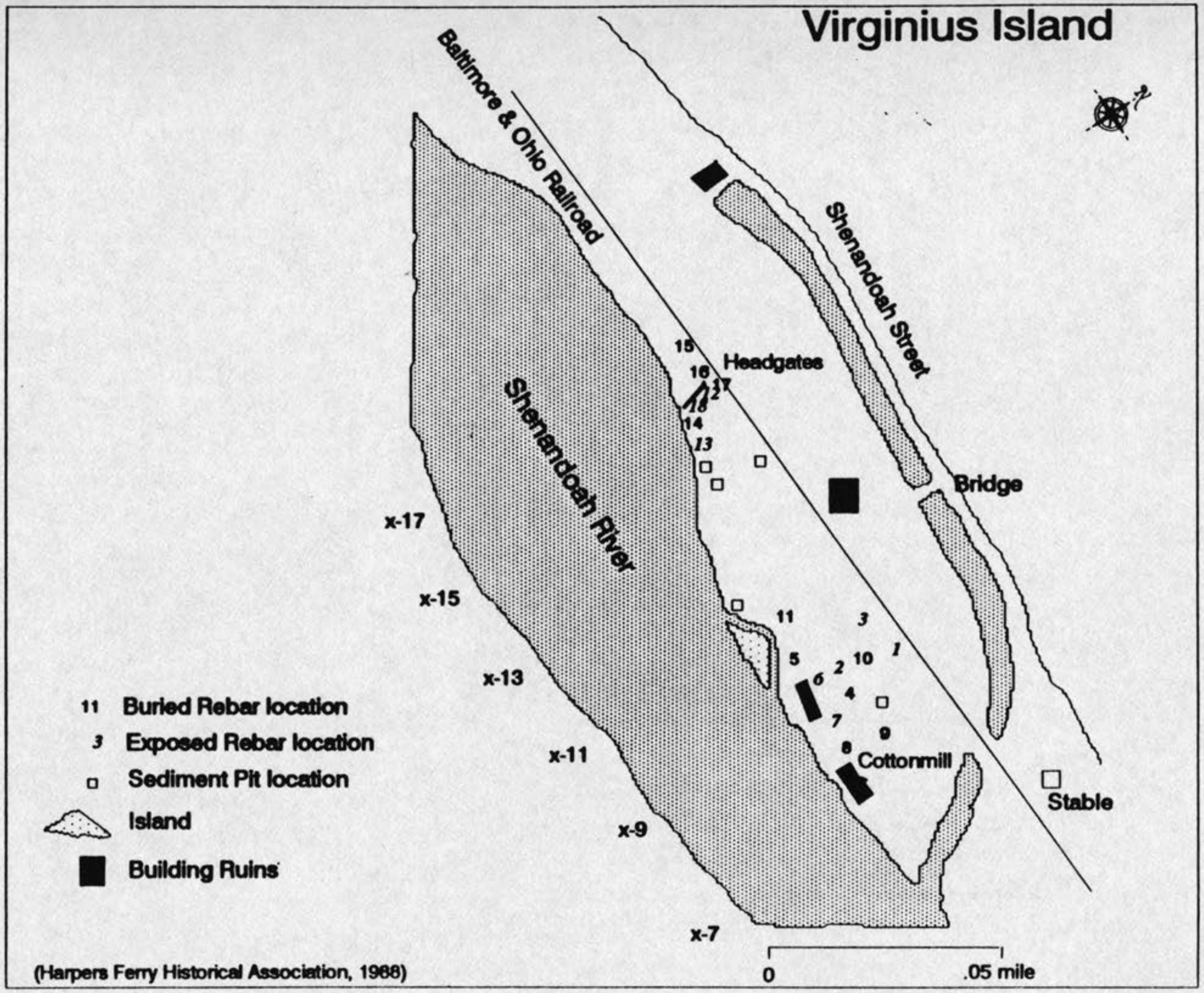


Figure 14. Schematic showing sediment pit and rebar locations (base-map from Harpers Ferry Historical Association, 1988).

relatively shallow depth and close proximity to the channel, coupled with the history of Virginius Island, the likelihood of these deposits being preserved for approximately 3,000 years is highly unlikely. It is much more probable that the dated charcoal fragments were re-worked remnants of much older deposits that have been re-transported by the present Shenandoah River. The small size of the charcoal fragments is also indicative of re-worked older charcoal (Blong and Gillespie, 1978).

Although site #2 is a much younger deposit (approximately 430 years BP) (Table 5), the accuracy of this date is also questionable. The Baltimore & Ohio Railroad was installed during the 1830's. Site #2, located directly adjacent to the bottom of the railroad berm, was very probably altered during railroad construction, particularly to the depth of the pit (pit depth was approximately 92 cm). Additionally, at approximately 30 cm depth, a plastic tile dating to the 1950's to 1960's was found. This artifact dates that stratigraphic unit as being between 31 to 41 years old, which is a reasonable estimate based upon the history and vegetative establishment of the island. In summary, based upon Virginius Island's industrial history, shallow soil depths, and frequency of inundation, the three radiocarbon ages are probably not representative of the true ages of the deposits. The best indicators of deposit age were found to be the plastic tile located at site #2, and the vegetative establishment of the area.

The rebar investigation located a total of 18 rebars: Eight of which were exposed, with the remaining ten being buried (Figure 14, Table 6). The amount of exposure ranged from a maximum of 19.5 cm to a minimum of being flush with the ground surface, whereas the depth of burial ranged from a maximum of 33.5 cm to a minimum of 1.5 cm (Table 6). The exposed rebars may produce erroneous measurements because several of them were installed directly into bedrock. The rebars may not have been originally emplaced flush with the rock surface, because of the difficulties installing rebar in bedrock. Without knowing the amount of original exposure, accurate determination of any additional exposure since installation would be very difficult; therefore, the estimates of rebar exposure may be inaccurate.

The rebar investigation showed areas of deposition and areas of erosion, but no readily apparent trends (Figure 14). There was no consistency in the spatial variation of sedimentation in either upstream versus downstream areas, or progressing laterally away from the channel. A possible explanation for this could be a result of the irregular topography of the island.

Since Virginius Island's decline in the early 1900's, the island has been left to restore itself naturally, with

Table 6. Results of rebar investigation. Amounts of burial or exposure indicated by - or +, respectively.

Rebar Number	Relative Location	Sedimentation
1	East part of island Near railroad	+(4.0 cm)
2	Midway between left channel edge & railroad	Flush with surface
3	East part of island Near railroad	+(3.5 cm)
4	Midway between left channel bank & railroad	-(1.5 cm)
5	Near Shenandoah left bank Near Valley Mills	-(13.5 cm)
6	East part of island Near Valley Mills	+(8.5 cm)
7	Downstream part of island Near left channel bank	Flush with surface
8	Most downstream point Near left channel bank	-(2.0 cm)
9	Midway between left channel bank & railroad	-(1.5 cm)
10	Midway between left channel bank & railroad	-(7.0 cm)
11	Near Shenandoah left bank at small island	-(33.5 cm)
12	At inlet of headgates	+(7.5 cm)
13	Downstream of headgates at extreme left channel edge	+(19.5 cm)
14	Downstream of headgates Near left channel edge	-(21.0 cm)
15	Northwest of headgates Near railroad	-(9.0 cm)
16	Due north of headgates Near railroad	-(21.0 cm)
17	Due east of headgates Near railroad	-(5.5 cm)
18	Due east of headgates, Between channel & railroad	+(7.5 cm)

minimal impacts from the Harpers Ferry National Historic Park. The numerous islands and canals established during the Industrial Era have become a reunited landmass. The canals have begun to gradually infill, though still existing as topographic lows, and the previously separated islands are becoming more cohesive. However, the pre-existing irregular topography of Virginius Island created during the 1800's is still imprinted on the present island morphology and topography, resulting in irregular patterns of sedimentation. Regardless of the irregularities in sedimentation, a maximum sedimentation rate of 2.8 cm/year, and a maximum erosional rate of 0.7 cm/year, occurred during the last twelve years. Neither of these estimates illustrate a rapid change in rates of sedimentation or erosion occurring on Virginius Island.

Comparison of the 1937, 1969, and 1991 aerial photographs show very minor amounts of channel change from the confluence of the Shenandoah and Potomac Rivers upstream to the Rt. 340 bridge. Figures 15, 16, and 17 are computer-generated overlays of the aerial photographs which illustrate the Shenandoah River pattern during the three years of comparison. Exact overlays could not be generated as a result of differences in scale, resolution, and initial angle at which the photographs were taken, as well as the quality of the photographs; however, the differences are minimal.

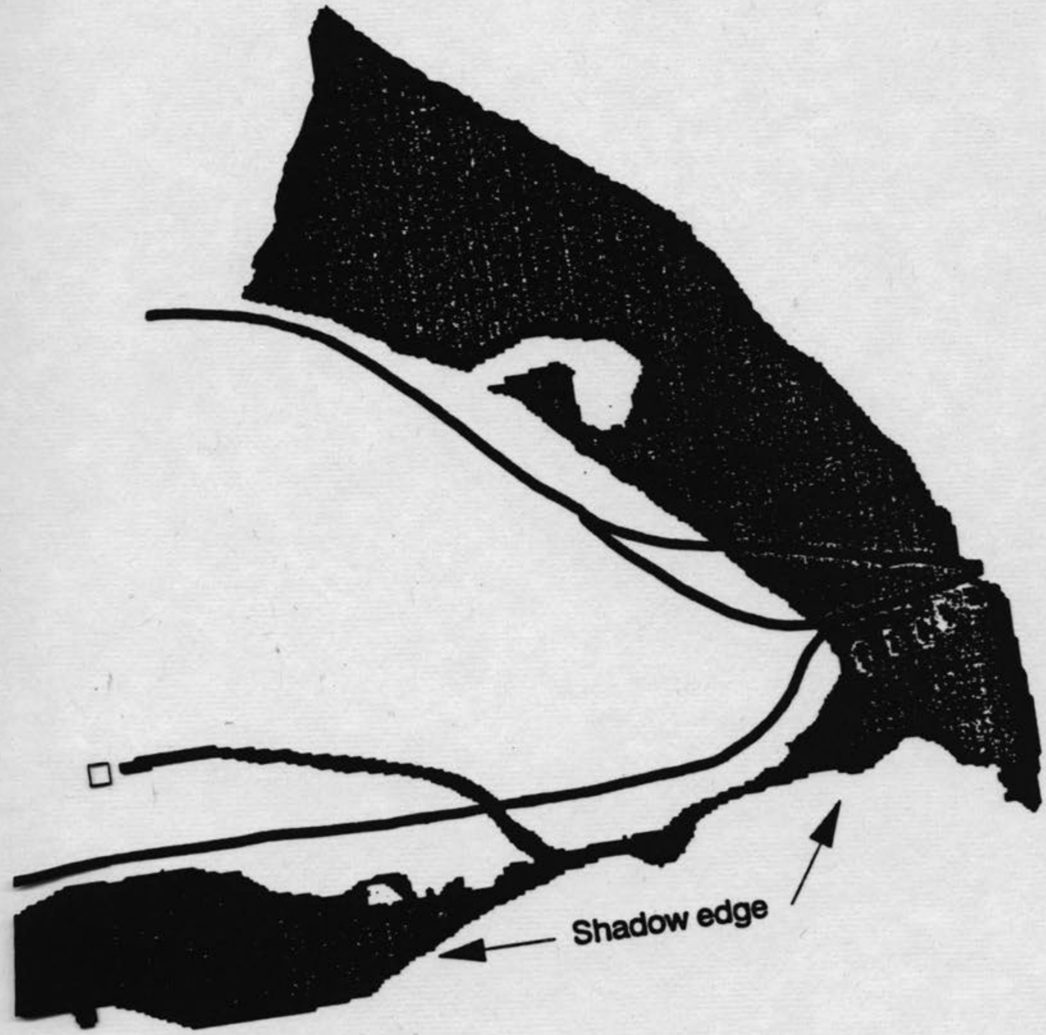


Figure 15. Computer generated overlay from a 1937 aerial photograph illustrating the Shenandoah River channel pattern in the vicinity of Harpers Ferry, West Virginia.

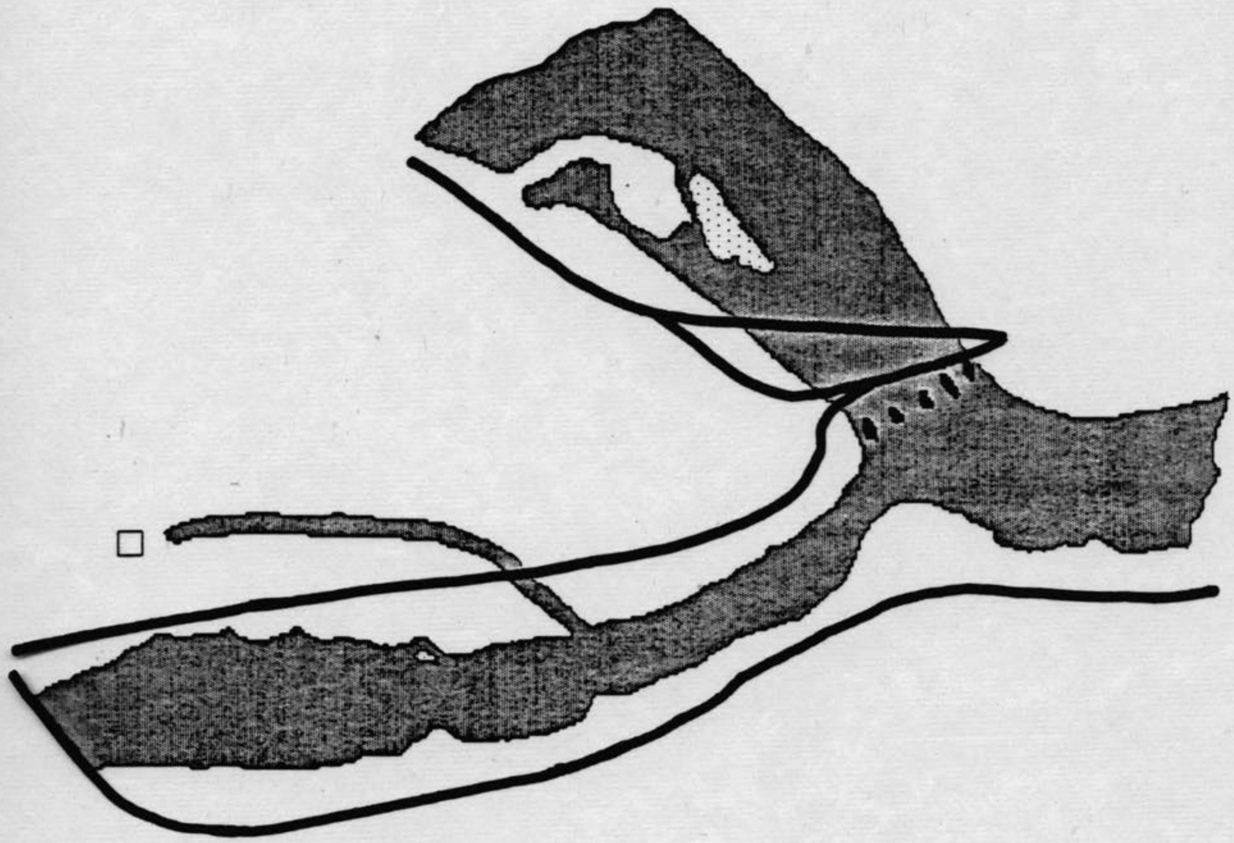


Figure 16. Computer generated overlay from a 1969 aerial photograph illustrating the Shenandoah River channel pattern in the vicinity of Harpers Ferry, West Virginia.

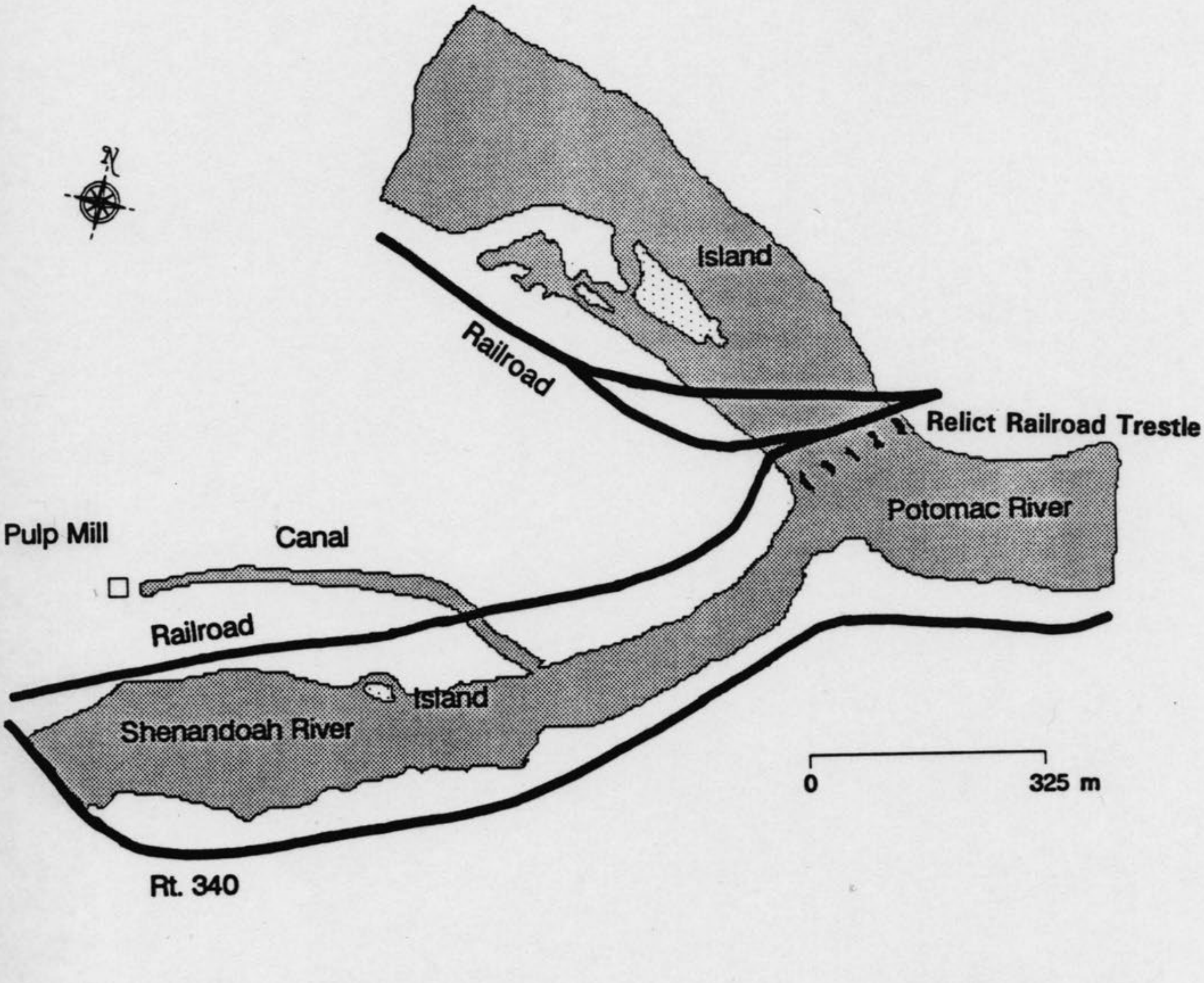


Figure 17. Computer generated overlay from a 1991 aerial photograph illustrating the Shenandoah River channel pattern in the vicinity of Harpers Ferry, West Virginia.

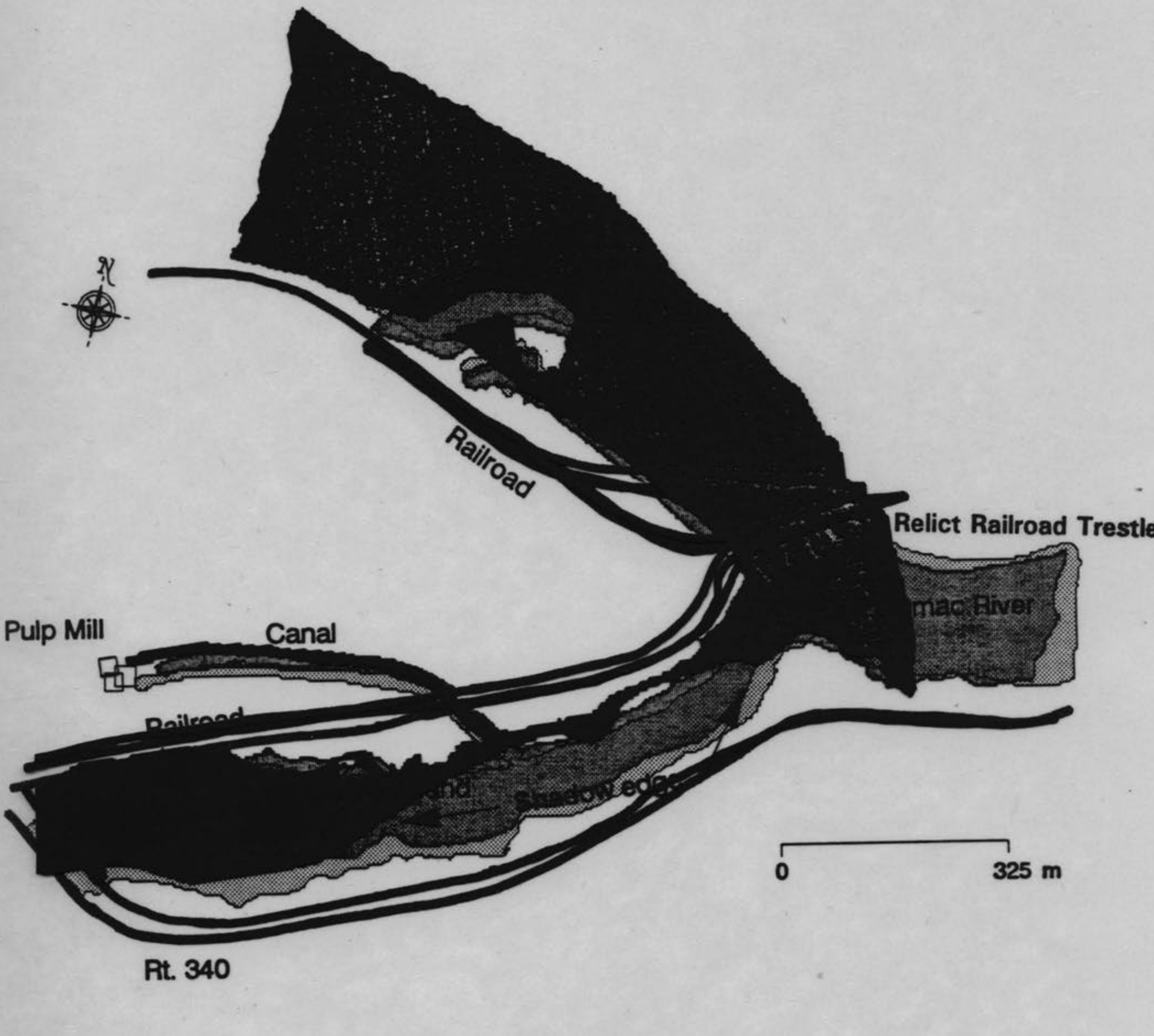


Figure 15. Computer generated overlay from a 1991 aerial photograph illustrating the Shenandoah River channel pattern in the vicinity of Harpers Ferry, West Virginia.

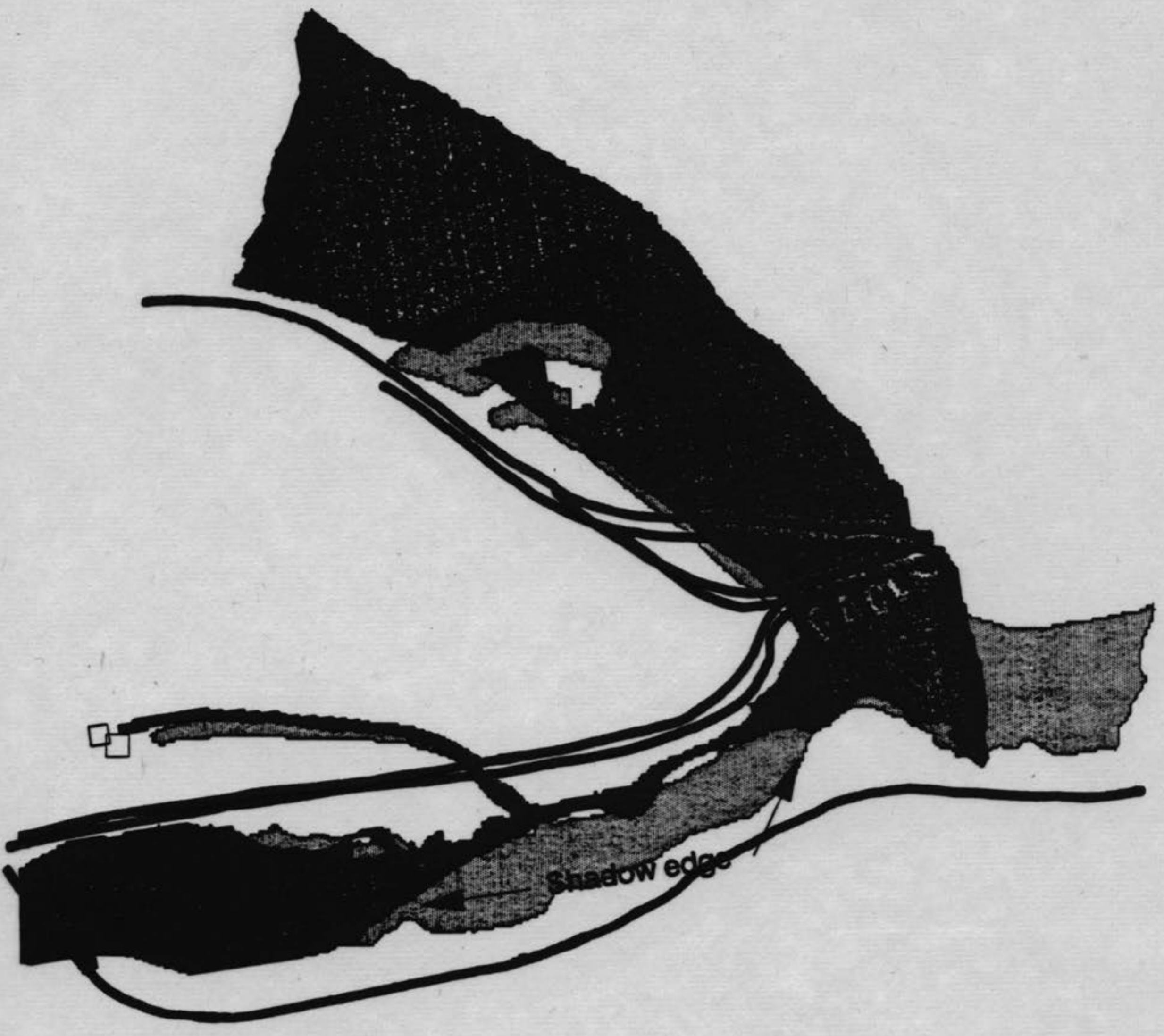


Figure 15. Computer generated overlay from a 1937 aerial photograph illustrating the Shenandoah River channel pattern in the vicinity of Harpers Ferry, West Virginia.

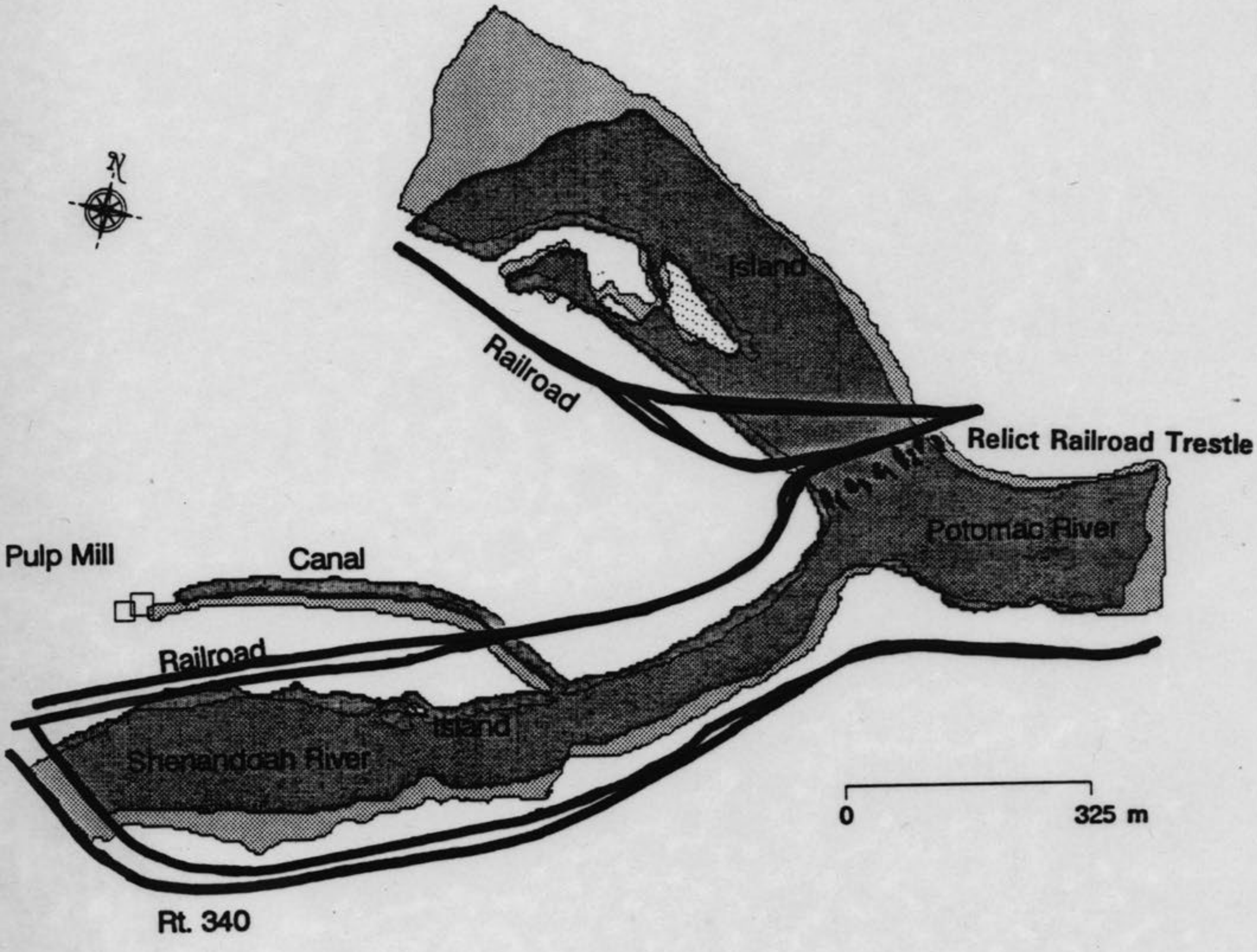


Figure 16. Computer generated overlay from a 1962 aerial photograph illustrating the Shenandoah River channel pattern in the vicinity of Harpers Ferry, West Virginia.

Unfortunately, the comparison of the 1937 and 1991 photographs was difficult due to the right bank of the Shenandoah River being obscured by shadows; however, the left bank could be compared (Figures 15, 17, and 18). The comparison showed minor amounts of left bank aggradation during the 54 years that have elapsed from 1937 to 1991. It should be emphasized that the resolution, scale, and photographic quality of the 1937 aerial photograph was less than that of the 1991 photograph. This could have resulted in any sand shoreline evident in the 1991 photograph being indistinct in the 1937 photo. Based upon the minor amount of sedimentation indicated by the comparison, coupled with the above inaccuracies, the over-all channel changes were minimal. If sedimentation is occurring, it is very probably in response to the vegetative establishment and reduced anthropogenic effects currently exerting control on the area.

Comparison of the 1969 and 1991 photographs illustrated an almost identical channel with some widening of the right bank occurring immediately downstream of the Rt. 340 bridge; however, the amount of widening is minimal and may have resulted from resolution discrepancies produced from vegetative obscurement of the right bank in the 1969 photograph (Figures 16, 17). All other channel areas remained nearly identical, with no noticeable sedimentation or erosion occurring.

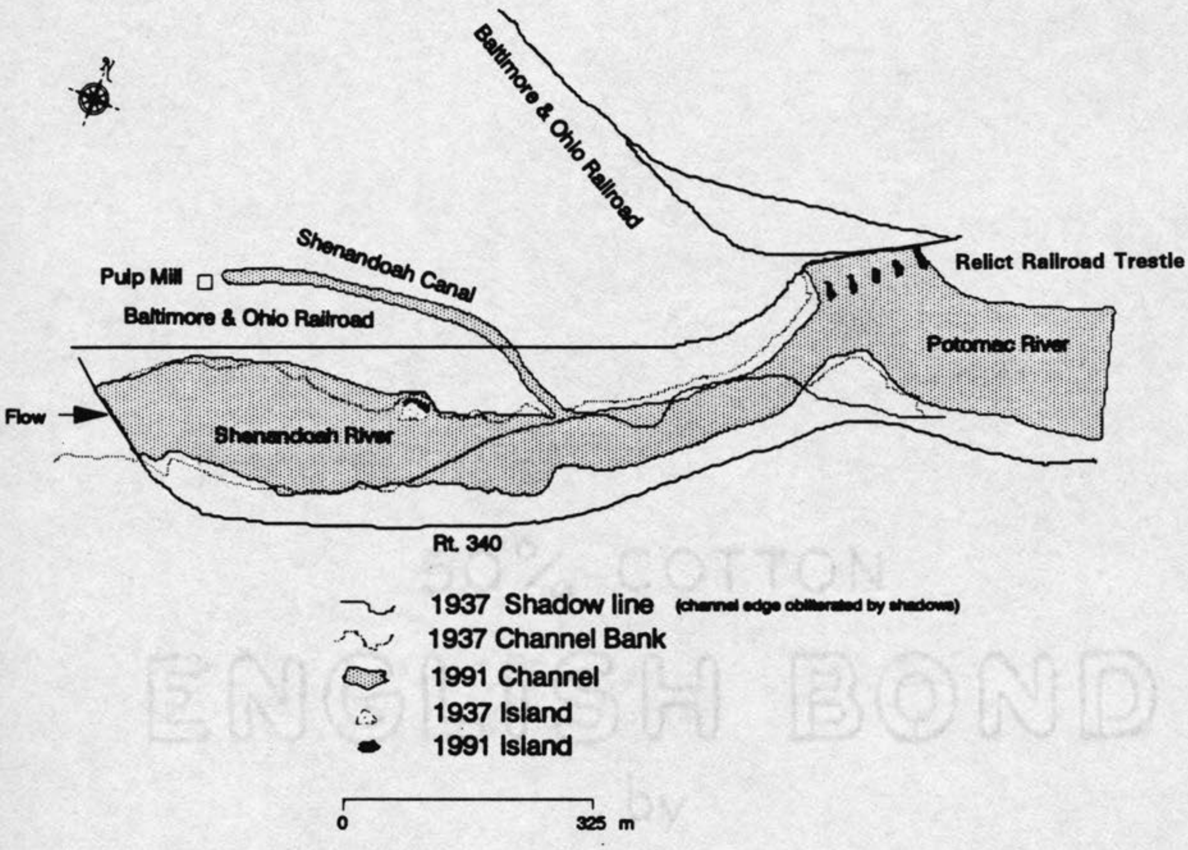


Figure 18. Summary comparison of the 1937 and 1991 overlays depicting channel changes through time.

The aerial photograph comparison from 1937 to 1991 showed minor to no channel changes occurring in the vicinity of Harpers Ferry, within the last 54 years (Figure 18). This is to be somewhat expected as a result of the bedrock control and vegetative establishment in the area. Both of these factors function to enhance and maintain channel stability over time.

In summary, the channel stability investigation including the flood deposit, rebar and aerial photograph investigations show the area to be relatively stable within the last 50 - 100 years. Small scale variations in sedimentation and erosion have occurred on Virginius Island, but on the larger spatial scale, channel variations have been minor. Although the total period of record encompasses the previous 244 years, this investigation does lend support to the assumption that the area has exhibited hydrologic stationarity for the period of record.

Water-Surface Profile Estimates

Stage estimation is a critical component of any paleohydrologic investigation. The accuracy of discharge estimates and frequency analysis is dependent upon the accuracy of the estimated stages. Periods of non-stationarity can bear inaccurate flood stage estimates, if those estimates were determined from the channel geometry during the period of stationarity. In addition, accurate stages can sometimes be very difficult to estimate from various sources of paleohydrologic data, due to the inherent variability of these data.

Stage estimates were determined for the majority of paleoflood indicators, excluding sedimentological indicators: Stage estimates were not necessary for these indicators due to none of them being slackwater deposits. However, some of the historical records, particularly those of the B&O Railroad Annual Reports, documented numerous flood dates, but no associated flood stages. In this case, no quantitative flood stages could be calculated. The remaining historical flood stages ranged from a minimum of 5.08 m to a maximum 10.97 m, occurring during the flood of 1889.

Flood stages, determined from the botanical and historical evidence, were compared to the computed water-surface profiles determined from the systematic record (Figure 19, 20, 21, and 22). By comparing the stages of these data, the accuracy of stage estimates by paleohydrologic data could be assessed. Although ring anomalies were not classified as high-quality botanical evidence and therefore not used in the flood-frequency analysis, they were included within the stage comparison to yield a more complete comparison of all types of botanical indicators.

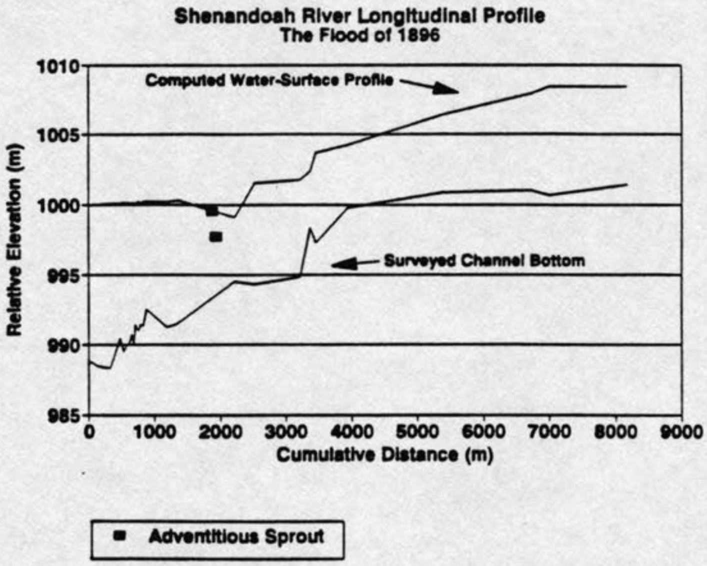


Figure 19. Comparison of the 1896 flood stage derived from paleoflood evidence versus the flood stage documented by the systematic record.

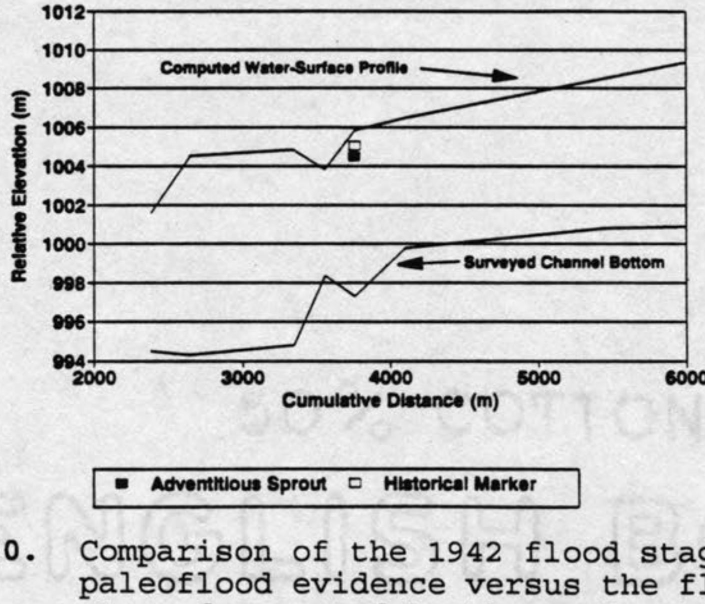


Figure 20. Comparison of the 1942 flood stage derived from paleoflood evidence versus the flood stage documented by the systematic record.

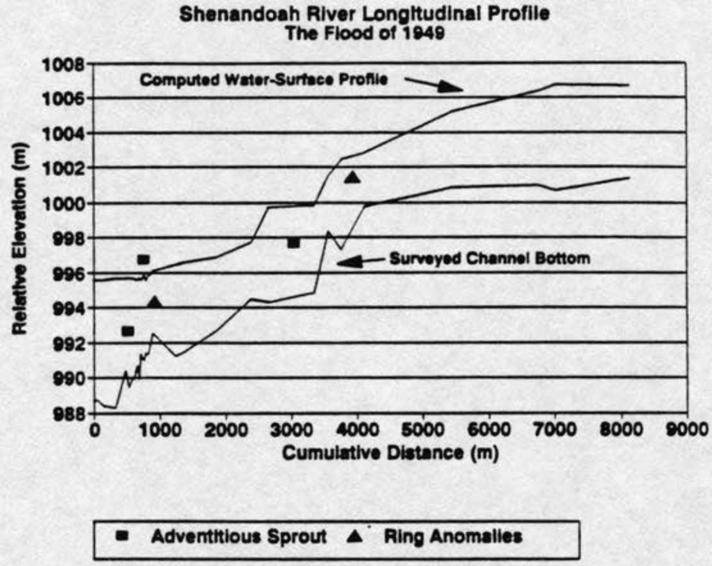


Figure 21. Comparison of the 1949 flood stage derived from paleoflood evidence versus the flood stage documented by the systematic record.

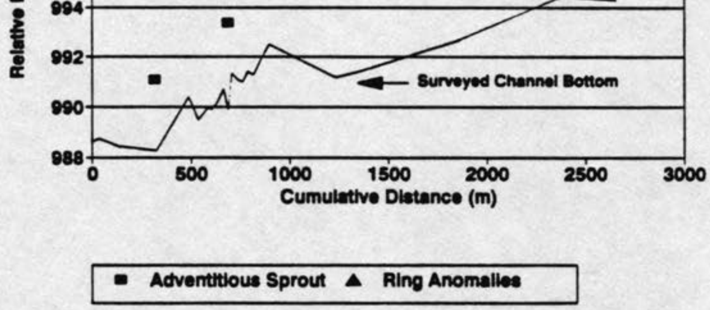


Figure 22. Comparison of the 1955 flood stage derived from paleoflood evidence versus the flood stage documented by the systematic record.

As shown in Figures 19-22, the paleoflood indicators did not establish a consistent or accurate flood stage. The degree of accuracy of each specific type of evidence is uncertain due to the lack of certain types of paleoflood data. However, the general data trend illustrates that the majority of paleoflood indicators yielded flood stages that were lower than the actual computed water-surface profile. Only two indicators yielded flood stages that were equal to or greater than the actual computed water-surface profile derived from the systematic record (Table 7). The explanations for the stage discrepancy vary according to the data source.

Historical Records:

The abundant written records facilitated the cross-referencing of qualitative stage estimates. Although occasional accounts of the same flood produced slightly different flood stages, the majority of flood stages from the various sources yielded very consistent flood stages that were within one to two meters of each other. This slight inconsistency is probably a result of the emotional condition of the flood observers. Often during floods, flood onlookers are in a state of fright and stress. This emotional condition could affect their judgement, thereby generating slightly high or low stage estimates. A larger

Table 7. Summary of paleoflood stage indicators. In all but one case, the flood stages determined from paleoflood evidence were equal to or lower than the flood stages documented by the systematic flood record.

The Paleoflood Stage vs. The Systematic Flood Stage

Date	PFS = SFS	PFS < SFS	PFS > SFS
1896	■	■	
1942		● ■	
1949		■ ▲	■
1955		▲ ■	

PFS = Paleoflood Stage
SFS = Systematic Flood Stage

■ = Adventitious Sprout
▲ = Ring Anomaly
● = Historical Markers

problem than the slight observer discrepancies was determining the exact location of the flood citing.

Harpers Ferry, as previously stated, is located at the convergence of the Potomac and Shenandoah Rivers. Floods that damaged Harpers Ferry were often the result of a Shenandoah flood, Potomac flood, or both. The written flood reports in newspapers, industrial records, and eyewitness accounts cite the maximum flood stages at Harpers Ferry, but do not specify to which river the citing was referring. Flood stages in the general area of Harpers Ferry could be the result of the rivers flooding independently or the cumulative effect of both rivers flooding simultaneously. It was necessary to assume that the stage citings were referring to the Shenandoah River flood stage in order to determine discharge estimates needed to conduct the flood frequency analysis, but this assumption could lead to erroneous stage estimates.

If the cited flood stage was actually for the Potomac River, and the Shenandoah River was not flooding, high stage estimates would be obtained. Additionally, if both rivers were flooding and the Shenandoah River experienced backflooding, elevated Shenandoah River stages would again be obtained. Even if both rivers did have identical water-surface elevations, this does not necessarily indicate that flood stage was identical because the Potomac River is slightly deeper than the Shenandoah. The degree of stage estimate error could not be determined from the available data, but all errors would yield over-estimates.

The historical evidence produced relatively accurate stage estimates. During the flood of 1942, an observer chiseled the flood stage into the bedrock channel wall (Figure 4). This flood stage was compared to the systematic flood stage record (Figure 20). The indicator generated an estimate that was approximately 1 m lower than the actual flood stage.

Botanical Indicators:

The accuracy of botanical stage indicators varies according to botanical type, with corrasion scars yielding the most accurate estimates (Hupp, 1988). Figures 19-22 illustrate the range of stages estimated by various types of botanical indicators for several floods. The botanical stage estimates range from being approximately 1 m high to approximately 6 m low.

A possible source of error could have been due to measuring to only the base of the tree, thereby estimating only a minimum stage. This would account for inaccuracies of 1-3 m low, but not inaccuracies 4-6 m low or 1 m high. This magnitude of error could only result from non-hydrologically created indicators, or inaccurate stage recordings by the botanical indicators themselves.

When a tree is damaged by flood water or the debris it carries, the tree is not necessarily recording the maximum peak flood stage. Flood-inclined trunks, which yield adventitious sprouts, often are inclined to a lower stage than the maximum flood stage. The amount of trunk inclination is a function of tree flexibility, size, and degree of establishment, as well as the stream power. The combination of these factors produces the amount of inclination, which may be large or small, but is not representative of the height of the flood waters.

A very large flood can totally inundate a tree, causing severe trunk inclination below the actual water surface. Eventually adventitious sprouts begin to grow. The stage of these sprouts will be extremely low in relation to flood stage. Contrarily, a moderate flood, causing a minor amount of trunk inclination, will yield adventitious sprouts which generate erroneously high flood stages. Additionally, botanical damage can occur during various flood stages.

Both corrasion scars and tilt sprouts can occur during rising and falling stages. In response, botanical indicators frequently record stages substantially lower than the peak flood stage as seen in Figures 19-22, although occasionally botanical indicators also yield erroneously high estimates.

Several corrasion scars, located within the study area, generated nearly identical stage estimates that exceeded the systematic flood record stage by approximately 15 m. Obviously, these indicators must be the result of non-hydrologic processes such as wind, people, pests, and other naturally occurring physical phenomena not related to flood waters.

Sedimentological Indicators:

The accuracy of these indicators could not be determined in this study, due to their limited presence. The majority of slackwater investigations have been conducted in the semi-arid regions of the western United States (Baker et al., 1988). This geographical location is conducive to the preservation of slackwater deposits due to the infrequent occurrence of large floods, and a very limited degree of vegetative establishment. As evident in this study, the eastern United States does not readily preserve slackwater deposits. This results from a very different climatic regime creating extensive vegetative cover which not only conceals the deposits, but also rapidly reworks the stratigraphy of the flood deposit through the effects of bioturbation.

Discharge Estimates

The accuracy of discharge measurements is contingent upon the accuracy of stage estimates from the paleohydrologic data. The botanical flood indicators were created by floods which occurred during the systematic record. Therefore, discharges associated with the year of the botanical indicators were obtained directly from the systematic record.

Historical record discharge estimates were determined by the Manning's equation and rating curve. The Manning's equation was used only to determine the maximum and minimum discharges associated with the historic record, whereas the rating curve was used to estimate the probable discharges for each flood occurring during the historical record and during periods of gaging record lapses (Rating Q, Table 8,9).

These discharge estimates are just that: estimates, due to the inherent error in each methodology. Error could result in the Manning's equation estimates from inaccurate determination of both the roughness coefficient and the water-surface slope associated with each discharge. It was assumed that the roughness coefficient was relatively small due to deep flood-waters. A change in this variable from 0.038 to 0.050 lowers the associated discharge estimates by 1,263 m^3s^{-1}. It was also assumed that the frictional slope of the water-surface was equal to the water-surface slope, which is not always correct and which can lead to substantial error (Webb and Rathburn, 1988).

A major source of error in the rating curve estimates was using erroneous stages both to construct the stage-

Table 9. Record lapse discharge values obtained from the rating curve.

Flood Year	Stage (m)	Rating Q (m^3/s)
1897	8.08	2,800
1897	5.45	1,120
1899	5.70	1,255
1902	7.44	2,450
1902	8.23	2,900
1908	5.64	1,200
1910	6.46	1,755
1913	5.64	1,200
1924	6.31	1,650
1924	5.79	1,300
1928	5.76	1,280

discharge relationship and from which the discharge values were obtained (as described previously in the section on water-surface profile estimates).

The stages used in the construction of the rating curve could have been erroneous due to the backflooding of the Shenandoah River. Normally, rating curves will predict increasing discharges with associated increases in stage. This was not the case for this rating curve. The floods of 1937 and 1976 had the same stages at Harpers Ferry, yet the associated discharges for the Shenandoah River ranged from 974 m^3s^{-1} to 1,398 m^3s^{-1}, respectively. During the flood of 1937 the Shenandoah underwent severe backflooding, resulting in elevated flood stages. This is just one example of the stage discrepancies due to the backflooding of the

Shenandoah River, but several others exist. These stage discrepancies could result in a non-representative rating curve. An additional problem with the flood stages was a disparity in flood dates.

In six out of the twenty floods used to generate the curve, the maximum flood stage recorded at Harpers Ferry was recorded one day earlier or later than the maximum discharge on the Shenandoah River at Millville. The reason for this disparity is unclear. It could be a recording error, or it could indicate that both rivers were flooding and that the Shenandoah River peaked a day later than the Potomac River. If the latter is true, the stage recorded at Harpers Ferry is not an accurate stage estimate for the Shenandoah River's discharge.

Although this rating curve does incorporate numerous sources of error, these errors are consistent with the errors incorporated into the historical record's stage estimates. In a normal flood-frequency analysis, all the above incongruities are undesirable, but in light of the same incongruities being incorporated in the historical stage estimates, this rating curve, although seemingly unorthodox, may provide the most accurate representation of a stage-discharge relationship for the historical data in the vicinity of Harpers Ferry. Obviously, this cumulative effect of errors is not desired; however, all the above inaccuracies will lead to over-estimation, which is more desirable than underestimation when conducting a flood frequency analysis.

The discharge estimates needed for the flood frequency analysis include the probable discharges (which have been obtained through the use of the rating curve) and the associated range within which these probable discharges could vary. By using the discharges obtained from the historical data as ranges in the flood frequency analysis, the error associated with their determination is minimized.

The range varied from the minimum to maximum flood discharge. The minimum flood stage was 5.48 m, while the maximum stage was 10.97 m. The associated discharges ranged from 1,150 m^3s^{-1} to 4,900 m^3s^{-1} according to the rating curve, whereas the Manning's equation estimates ranged from 1,300 m^3s^{-1} to 8,112 m^3s^{-1}. The minimum values are relatively consistent, but the maximum discharge estimates vary by 6,812 m^3s^{-1}. The accuracy of either estimate is extremely questionable; therefore, the two estimates were averaged and this value (6,506 m^3s^{-1}) was used as the maximum discharge estimate.

Using the average of these two values was justified by comparing this value to the maximum discharge recorded at Millville for the Shenandoah River, which occurred in October of 1942. At Harpers Ferry this flood had a stage of 10.29 m with an associated discharge of 6,509 m^3s^{-1}. This discharge could only be exceeded if a stage greater than

10.29 m occurred at Harpers Ferry in response to the Shenandoah River flooding independently. This never happened. The actual stage of 10.29 m was exceeded once during the flood of 1889, but in this particular instance both rivers were flooding, leading to backflooding of the Shenandoah River and elevated flood stages.

Flood Frequency Analysis

Flood frequency analyses were conducted independently for the systematic, paleoflood and total period of record. As seen in Figure 23, the initial discharge values associated with the 2-, 5-, 10-, and 20-year events are relatively similar. The discharges associated with the 20-year event, for example, ranged from 2,169 m^3s^{-1} to 3,428 m^3s^{-1}, for the paleoflood and systematic record, respectively. However, as the floods become less frequent the associated discharges begin to vary, ranging from 2,843 m^3s^{-1} to 9,418 m^3s^{-1} associated with the 1,000-year event again for the paleoflood and systematic record, respectively.

The total period of record analysis yields values between the upper and lower estimates associated with the systematic and paleoflood records, respectively. This is to be expected, since this analysis is a summation of both the paleoflood and systematic records.

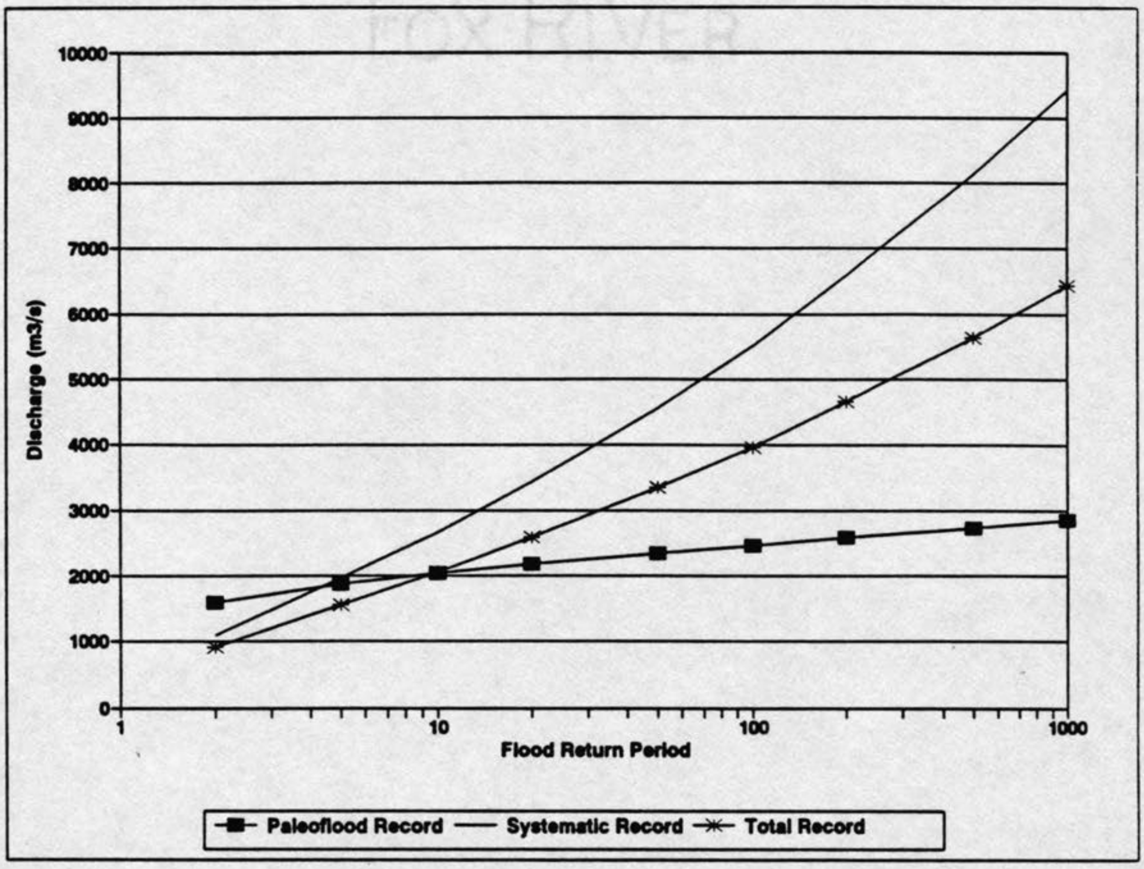


Figure 23. Comparison of the lognormal flood frequency analysis conducted for the systematic, paleoflood, and total period of record.

The differences between the systematic and paleoflood records are statistically significant ($p=0.01$). This could indicate that the two flood populations do not exhibit stationarity for the duration of the flood record. However, this difference could be the result of data classification, the number and magnitude of thresholds used, and the frequency distribution chosen to analyze the data.

As seen in Table 10, flood magnitudes can be classified as 'E', if the event's magnitude is to be considered by a known value, 'R', if an event's magnitude will be described by a range, or 'L', if an event's magnitude will be described by a lower bound (Stedinger et al., 1988a). MAX has been compiled to accommodate for only 20 events classified by ranges ('R') and only 25 events classified by lower bounds ('L'). This created problems, particularly for the total period of record analysis. Discharge classification had to be manipulated to meet the above criteria specified by the model. This could result in inaccurate flood frequency predictions.

As seen in Figure 24, changing the classification of flood magnitudes from 'R' (range analysis) to 'E' (value analysis) for the paleoflood record increased the discharge associated with the 1,000-year event from 2,843 m^3s^{-1} to 6,521 m^3s^{-1}. Obviously, data must be classified properly to yield accurate results. In addition to data classification, threshold determination is another important parameter which

Table 10. Display of sample input file for MAX. E indicates data entered as values, whereas R indicates data entered as ranges. Note, flood events are listed in descending order. Discharge is shown in m^3s^{-1}.

Date	Probable Q Magnitude	Q Range Lower	Q Range Upper	Data Classification
1942	6509	N/A		E
1889	4900	1150	6506	R
1936	4273	N/A		E
1985	4019	N/A		E
1852	3870	1150	6506	R
1870	3595	1150	6506	R
1877	3490	1150	6506	R
1924	3368	N/A		E
1843	3250	1150	6506	R
1862	3250	1150	6506	R
1896	2972	N/A		E
1972	2915	N/A		E
1865	2900	1150	6506	R
1902	2900	1150	6506	R
1955	2802	N/A		E
1846	2800	1150	6506	R
1897	2800	1150	6506	R
1810	2750	1150	6506	R
1748	2640	1150	6506	R
1937	2473	N/A		E
1861	2400	1150	6506	R
1864	2370	1150	6506	R

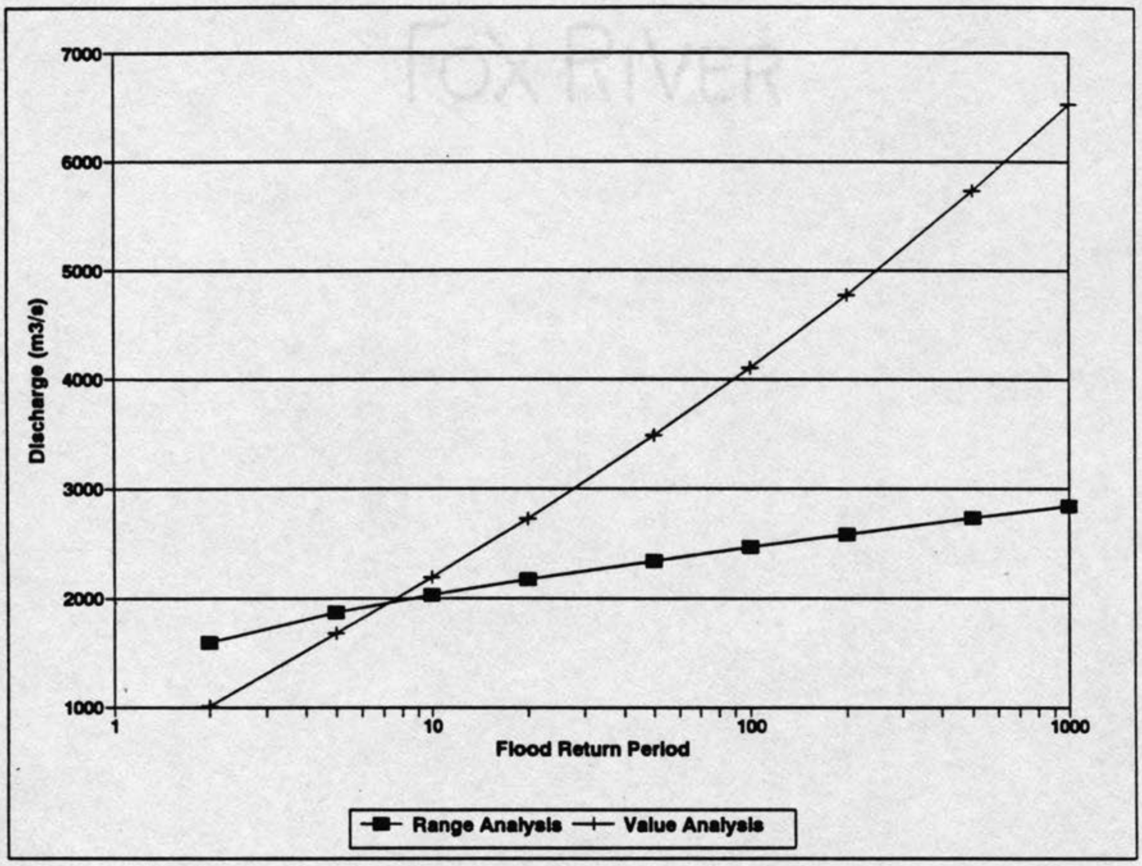


Figure 24. Comparison of flood frequency analyses using identical data sets with the exception of flood classification. In the value analysis all floods were denoted by 'E', whereas in the range analysis all floods were denoted by 'R' with the exception of two 'E' denoted floods (MAX requires at least two events classified as 'E' events).

ultimately effects the resulting flood prediction.

During a manipulation of the data base for the total period of record, the number of thresholds was decreased from two to one. The duration of the data set, the classification, magnitude, and number of floods remained constant, yet the 10-, and 1000-year events dropped from 2,052 m^3s^{-1} to 1,718 m^3s^{-1}, and from 6,447 m^3s^{-1} to 6,098 m^3s^{-1}, respectively. This indicates that the frequency analyses are also sensitive to threshold determination.

Another source of variability incorporated in the model is the various flood frequency distribution options. MAX offers numerous flood frequency distributions including the normal/lognormal, 2-parameter lognormal, 3-parameter lognormal, Pearson type 3, log-Pearson type 3, Gumbel and GEV (Generalized Extreme Value), Index log-Pearson, and B17 (USWRC, 1982; Stedinger et al., 1988a).

Numerous distributions may fit a data set, but the objective is to determine the distribution which represents the data set most accurately. This ultimately results in the most accurate flood frequency estimates. Figure 25 illustrates the ranges of values obtained from one data set which was analyzed by differing frequency distributions.

The total period of record was analyzed using four different frequency distributions; the lognormal, the 3-parameter lognormal, the GEV, and the log-Pearson type 3.

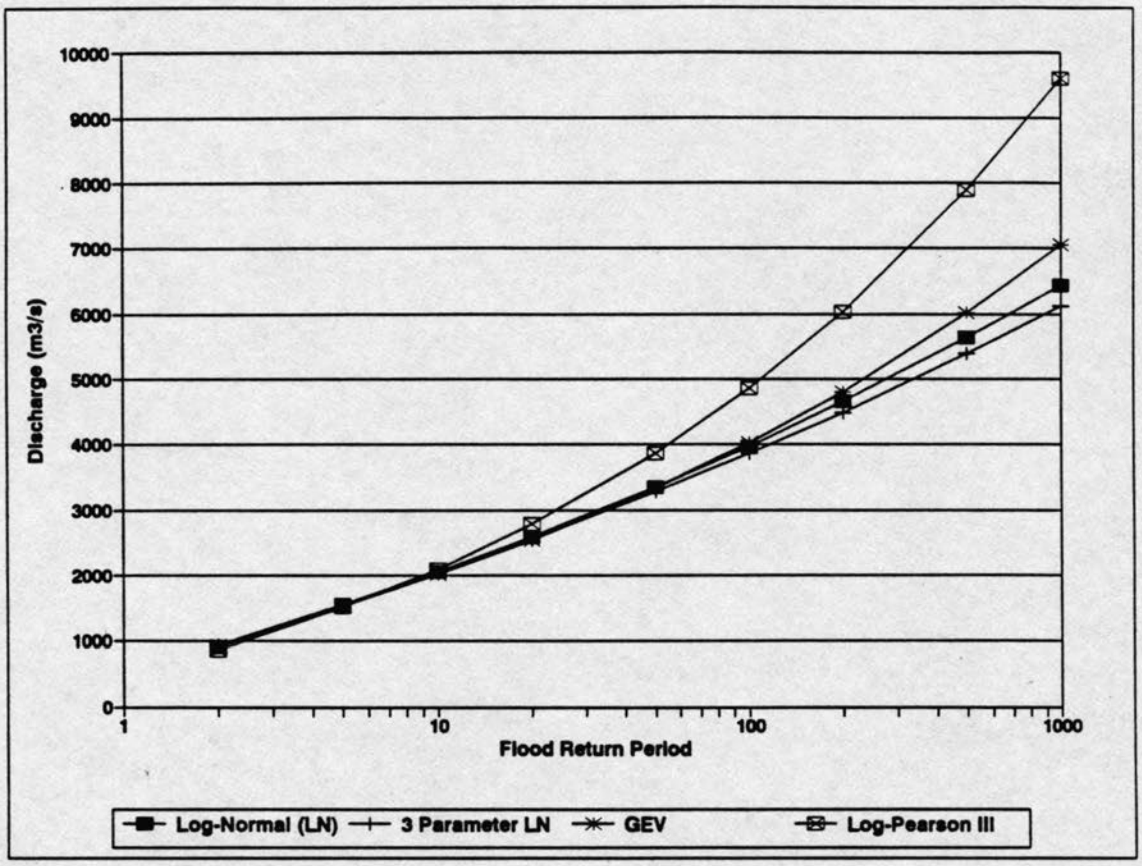


Figure 25. Comparison of various flood frequency distributions used to analyze the total period of record.

All distributions resulted in similar values associated with high frequency events. The disparity in discharges is seen most clearly in the long recurrence interval events associated with large discharges. For the 1,000-year event, discharges ranged from 6,447 m^3s^{-1} for the lognormal distribution, to 9,598 m^3s^{-1} determined by the log-Pearson type 3 distribution (Figure 25).

It is outside the scope of this thesis to analyze the various distributions and determine which yields the best fit, but based upon the slightly positive regional skew coefficient associated with the study area, the GEV or 3-parameter lognormal distributions (which use slightly positive skew coefficients in their distributions) should demonstrate the best-fit results. Unfortunately, these frequency distributions did not fit all the data sets. For ease of comparison, a distribution which fit all data sets was chosen; this was the lognormal frequency distribution.

In light of the above complexity associated with the results of the model, a confident determination of the existence of stationarity or non-stationarity cannot be made. Additionally, the flood frequency analysis conducted for the systematic, paleoflood and total period of record is only a preliminary study to illustrate the capacities of the model. To use any of the results generated by MAX, a detailed and thorough investigation which incorporates and analyzes the various complexities associated with MAX should be performed.

CHAPTER V

CONCLUSIONS

1. The flood record was extended through the use of paleoflood data from 1893 to 1748. The total period of record encompassed 244 years.

a. Historical data extended the systematic flood record from 1893 to 1748. The majority of historical data were qualitative and obtained from written documents.

b. The botanical data did not extend the systematic flood record due to intense anthropogenic influences occurring in the study area. The botanical data extended from 1896 to 1955.

c. The sedimentological data were limited due to the climatic regime of the study area, and could not be used to extend the systematic flood record.

Paleoflood indicators, including historical, botanical, and sedimentological indicators are all very useful, but different environments are conducive to recording data in different forms. For instance, in this study, slackwater deposits were limited due to the rapid reworking of the soil profile by weathering and vegetative establishment resulting from the humid-temperate climatic regime; in contrast, this climatic regime was ideal for the dense establishment of vegetation which enhanced the availability of botanical indicators. Unfortunately, due to the extensive systematic data and limited tree age in response to extensive human deforestation, these botanical indicators did not extend the existing record. However, because of the early colonization of the area of study, historical records were extremely abundant and did extend the systematic record by 155 years.

In more arid environments, slackwater deposits have yielded the majority of paleoflood evidence (Baker, 1978). In this type of environment, decreased rainfall inhibits weathering and vegetative establishment, thereby preserving the sedimentary stratigraphy of flood deposits, while decreasing the availability of botanical flood indicators. Although botanical indicators may be less abundant in more arid environments, if botanical indicators are found, they often yield a longer period of record due to the longer life-span of the tree species in this environment. Semi-arid to arid environments are often dominated by conifers, which typically live longer than deciduous trees of eastern environments (Burns and Honkala, 1990).

2. The channel stability investigation, including the flood deposit, rebar, and aerial photograph comparison, illustrated that the area of study has undergone minimal amounts of change over the last 50 - 100 years. Small scale changes in sedimentation and erosion have occurred on

Virginius Island, but larger scale channel changes have been minimal.

3. The accuracy of paleoflood indicators is variable, and a universal rule stating which indicator yields the most reliable information cannot be established. Historical records did produce stage estimates that were accurate to within one to two meters. Botanical indicators produced stage estimates with varying degrees of accuracy. The majority of indicators yielded under-estimates of flood stage, but over-estimates also occurred. The accuracy of sedimentological data could not be assessed due to their limited existence. Based upon this information, historical records, in this study, produced the most accurate results, but I must emphasize that the accuracy of each type of indicator is site-specific depending upon the site hydraulics, climatic regime, and anthropogenic history. In response to this variability, each paleoflood study should be carefully scrutinized for possible sources of error, and no data source should be considered as consistently yielding the same degree of accuracy.

4. Discharge estimates obtained for the paleoflood indicators ranged from a minimum of 750 m^3s^{-1} to a maximum of 4,900 m^3s^{-1}.

5. The flood frequency analysis conducted using MAX was only a preliminary investigation to illustrate the applicability of the model to paleoflood data; therefore, no conclusive results were obtained.

MAX integrates information from systematic, historic, botanic, and sedimentological information in the flood frequency analysis. This model allows ranges and thresholds to define paleoflood events as well as missing floods. This is extremely valuable when using paleoflood information due to the uncertainties associated with paleoflood discharge values and the sometimes incomplete paleoflood chronology. Unfortunately, the model is very complicated and difficult to use. It is also limited in the amount of data it can analyze. Another complication with the model is in the variety of frequency and data distributions which the model can analyze.

The model is capable of analyzing data using a variety of flood frequency distributions. Obviously, the model's output is dependent upon the frequency distribution selected. Therefore, to maximize the precision and efficiency of the model's output, an experienced hydrologist with a substantial background in statistics should analyze the outputs of various probability distributions to decide which distributions yield the most representative results.

Additionally, MAX is very sensitive to the positioning of the various thresholds and the classification of data.

To accurately use the model, several outputs should be generated using various threshold levels and data classifications to determine the most representative threshold magnitude.

Paleoflood indicators can be essential to flood frequency analysis. By increasing the period of record over which the analysis will be conducted, the accuracy of the analysis will be increased (however, this is again dependent upon the accuracy of the indicators)(Stedinger and Cohn, 1986; Cohn, 1986). The most beneficial paleoflood studies, from a flood frequency standpoint, would consist of sites with little to no systematic data, or those sites which can increase the current data base by thousands of years with paleoflood indicators. In these cases, the flood-frequency distribution will be significantly effected by the paleoflood information. However, if limited paleoflood information is used in conjunction with an already large systematic record, the resulting flood frequency distribution will be nearly identical (Stedinger, pers. comm., 1992). In studies such as this, paleoflood information serves only to increase the confidence of the standard flood frequency analyses.

Paleohydrologic information can be very useful to flood-frequency analysis. It serves as a relatively inexpensive method for augmenting a limited systematic record or for supplying a flood record if no systematic data are available. This latter usage of paleoflood information is extremely valuable if development plans need an immediate flood frequency analysis. A gage could be installed, but decades would need to pass before any flood frequency estimates could be determined from these data. A regional flood frequency analysis could also be conducted, but at best this methodology yields only approximate estimates. Paleoflood information is presently available, and ready to be analyzed (Cohn, pers. comm., 1992).

CHAPTER VI

RECOMMENDATIONS

This study addressed the use of paleoflood indicators to increase the existing systematic record in the eastern United States. Currently, the majority of paleoflood studies have been conducted in semi-arid to arid environments of the western United States, due to the emphasis being placed upon slackwater analysis. However, paleoflood investigations can also be extremely valuable for flood reconstruction in the humid-temperate environments of the eastern United States, if the emphasis of the studies is slightly different.

The following recommendations are suggested for paleoflood investigations being conducted in humid-temperate environments.

1. Paleoflood studies should incorporate botanical, sedimentological, and historical research, but the underlying assumption of finding slackwater deposits should be eliminated. Datable flood deposits may be abundant, but if these are recent deposits this does not constitute a slackwater investigation and will not aid in enhancing the systematic data. If an assumption must be made about what

type of evidence will dominate the investigation, assume it to be historical and botanical data.

2. Due to the extensive vegetative cover (often in the form of poison ivy and stinging nettles) attempts should be made to conduct the study before leaf emergence in the spring. This will not only make the job more enjoyable for the field investigators, but will also allow flood features such as potential slackwater deposits, flood debris, and botanical damage to be much more visible.

3. In response to the inaccurate stage predictions of the botanical indicators, it is only necessary to determine the elevation of the tree base, unless a scar is found. The elevation of the scar should be measured in addition to the elevation of the tree base. Additionally, the assumption of flood damage must be substantiated by several indicators.

4. The botanical investigation should concentrate on ring-porous species, such as ash, because diffuse porous species are usually extremely difficult to analyze.

5. A reasonable assessment of the expected results is absolutely necessary before embarking upon this type of study. If the study objective is to increase the existing systematic data base for a more accurate flood frequency analysis, the extent of the systematic record should be considered first. If an extensive systematic record is available, another 100-200 years of paleoflood data will not significantly effect the frequency distribution of the

systematic record (Stedinger, pers. comm., 1992; Hosking and Wallis, 1986), resulting in an unproductive investigation.

6. Currently, there are many shortfalls associated with MAX, but this should not inhibit its usage. However, this is not the type of model that an inexperienced hydrologist should use. A thorough understanding of the various flood frequency distributions and the statistical principles underlying the model itself is mandatory to obtain accurate results from this model.

REFERENCES

Baker, V.R. 1978. Large-scale erosional and depositional features of the Channeled Scabland. In, V.R. Baker, and D. Nummedal, eds., "The Channeled Scabland." National Aeronautics Space Administration, Washington, D.C., 81-115.

Baker, V.R. 1987. Paleoflood hydrology and extraordinary flood events. Journal of Hydrology 96: 79-99.

Baker, V.R. 1098. Magnitude and frequency of paleofloods. In, K. Beven and P. Carling, eds., "Floods: Hydrological, Sedimentological and Geomorphological Implications," John Wiley & Sons Ltd, 171-183.

Baker, V.R. and Bunker, R.C. 1985. Cataclysmic late Pleistocene flooding from glacial Lake Missoula: A review. Quaternary Science Review 4: 1-41.

Baker. V.R., Kochel, R.C., and Patton, P.C., eds. 1988. Flood geomorphology. Wiley Interscience, New York, 503 p.

Baker, V.R., Pickup, G. and Polach, H.A. 1983. Desert paleofloods in central Australia. Nature 301: 502-504.

Bernier, J., Miquel, J.,Lebosse, A., and Griffet, A. 1986. Use of additional historical information for estimation and goodness of fit of flood frequency models. Paper presented at the International Symposium on Flood Frequency and Risk Analysis, Louisiana State University.

Blong, R.J. and Gillespie, R. 1978. Fluvially transported charcoal gives erroneous ^{14}C ages for recent deposits. Nature 271: 739-741.

Bretz, J H. 1925. The Spokane flood beyond the channeled scablands. Journal of Geology 33: 617-649.

Bretz, J H. 1929. Valley deposits immediately east of the channeled scablands of Washington. Journal of Geology 37: 393-427.

Bryan, B.A. and Hupp, C.R. 1984. Dendrogeomorphic evidence of channel morphology changes in an east Tennessee coal area stream. EOS, Transactions American Geophysical Union 65: 891.

Bunker, R.C. 1982. Evidence of multiple late Wisconsin floods from glacial Lake Missoula in Badger Coulee, Washington. Quaternary Research 18: 17-31.

Burns, R.M. and Honkala, B.H., tech. coords. 1990. Silvics of North America: 1. Conifers. Agricultural Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, D.C. vol. 1, 674 p.

Burns, R.M. and Honkala, B.H., tech. coords. 1990. Silvics of North America: 2. Hardwoods. Agricultural Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, D.C. vol. 2, 877 p.

Cardwell, Dudley H., Erwin, Robert B., and Woodward, H. P. 1968. Geologic map of West Virginia: West Virginia Geological and Economic Survey, 2 sheets.

Cleaveland, M.K. 1980. Dating tree rings in Eastern United States. Virginia Polytechnical Institute State University. FWS-2-80, 110-124.

Chen, C.-C., Yeh, Y., and Tan, W. 1974. The important role of historical flood data in the estimation of spillway design floods. Peking, China, 15 p.

Chow, V.T. 1964. Handbook of applied hydrology. McGraw-Hill, New York.

Chow, V.T. Eliassen, R., King, P.H. and Linsley, R.K. 1982. "McGraw-Hill series in water resources and environmental engineering," McGraw-Hill, New York, 107-114.

Condie, R., and Lee, K. 1982. Flood frequency analysis with historic information. Journal of Hydrology 58(1/2): 47-61.

Condie, R., and Pilon, P.J. 1983. Fitting the Log-Pearson Type III distribution to censored samples: An application to flood frequency analysis with historic information. Proc. of the 6th. Canadian Hydrological Conference, Ottawa, Canada, 11-22.

Conway, M. 1981. "Harpers Ferry - Time remembered," Carabelle Books, Reston Virginia, 159 p.

Costa, J.E. 1978. Holocene stratigraphy in flood frequency analysis. Water Resources Research 14: 626-632.

Costa, J.E. 1983. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. Geological Society of America Bulletin 94: 986-1004.

Costa, J.E. 1984. Fluvial paleoflood hydrology. Transaction American Geophysical Union 65: 890.

Craig, T.L. 1990. Report from field and research studies of geomorphology and geology of Virginius Island and Shenandoah River, Harpers Ferry National Historic Park, WV. Internal Report, Water Resources Division, Applied Research Branch, National Park Service. Ft. Collins, Colorado, 8 p.

Craig, T.L. and Reed, B. 1990. Scope of work for paleoflood, geomorphic and hydraulic studies of the impact of flooding on Virginius Island, and for Virginius Island flood mitigation studies, Harpers Ferry National Historic Park. Internal Report, Water Resources Division, Applied Research Branch, National Park Service. Ft. Collins, Colorado, 7 p.

Dalrymple, T. and Benson, M.A. 1967. Measurement of peak discharge by the slope-area method. Technical Water Resource Research Division (U.S. Geological Survey), Book 3, Ch. A-2.

Ely, L.L. and Baker, V.R. 1985. Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona. Physical Geography 5: 103-126.

Ely, L.L., Enzel, Y., O'Connor, J.E., and Baker, V.R. 1991. Paleoflood records and risk assessment: Examples from the Colorado River Basin. NATO Advanced study Institute "Risk and Reliability in Water Resources and Environmental Engineering" Porto Carras, Greece. 4 p.

Everitt, B.L. 1968. Use of cottonwood in an investigation of the recent history of a floodplain. American Journal of Science 266: 417-439.

Fritts, H.C. 1976. Tree rings and climate. Academic Press, London, 567 p.

Gilbert, D. 1990. A walkers guide to Harpers Ferry, West Virginia. Pictorial Histories Publishing Company, Charleston, West Virginia, 88 p.

Gregory, K.J. 1976. Lichens and the determination of river channel capacity. Earth Surface Processes 1:273-285.

Harrison, S.S. and Reid, J.R. 1967. A flood-frequency graph based on tree-scar data. Proceedings North Dakota Academy of Science 21: 23-33.

Hazen, A. 1914. Storage to be provided in the impounding reservoirs for municipal water supply. Trans. Am. Soc. of Civil Engineers 7: 1547-1550.

Helley, E.J. and LaMarche, V.C., Jr. 1968. December 1964, A 400-year flood in northern California. U.S. Geological Survey Professional Paper 600-D, 34-37.

Helley, E.J. and LaMarche, V.C., Jr. 1973. Historic flood information for northern California streams from geological and botanical evidence. U.S. Geological Survey Professional Paper 485-E, 1-16.

Hosking, J.R.M. and Wallis, J.R. 1986. Paleoflood hydrology and flood frequency analysis. Water Resources Research 22(4): 543-550.

Hupp, C.R. 1986. Botanical evidence of floods and paleoflood frequency. Paper presented at the International Symposium on Flood Frequency and Risk Analysis, Baton Rouge, Louisiana, May, 1986.

Hupp, C.R. 1988. Plant ecological aspects of flood geomorphology and paleoflood history. In, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., "Flood geomorphology," Wiley, New York, 335-356.

Hydrologic Engineering Center. 1982. HEC-2 Water Surface Profiles; Users Manual. U.S. Army Corps of Engineers.

Janssen, Q. 1985. Harpers Ferry Floods! Specialty Binding and Printing Company, Shepherdstown, West Virginia, 71 p.

Jarrett, R.D. 1984. Evaluation of methods of estimating paleofloods on high-gradient streams. EOS, Transactions of American Geophysical Union 65: 893.

Jarrett, R.D. 1989. Paleohydrology and its value in analyzing floods and droughts. National Water Summary 1988-89, Floods and Drought, U.S. Geological Survey Water-Supply Paper 2375, 105-116.

Kite, J.S. and Linton, R.C. in press. Depositional aspects of the November 1985 flood on Cheat River and Black Fork, West Virginia. U.S. Geological Survey Professional Paper, 56 p.

Kochel, R.C. and Baker, V.R. 1982. Paleoflood hydrology. Science 215: 353-361.

Kochel, R.C. and Baker, V.R. 1988. Paleoflood analysis using slackwater deposits. In, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., "Flood geomorphology," Wiley, New York, 357-376.

Komar, P.D. 1988. Sediment transport by floods. In, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., "Flood geomorphology," Wiley, New York, 97-112.

Larrabee, E.M. 1961. Report of the second season of exploratory archeological excavations conducted at the U.S. Rifle Works, Lower Hall Island, Harpers Ferry National Monument, Harpers Ferry, West Virginia from June 23 through July 6, 1960. United States National Park Service, Harpers Ferry, West Virginia, 35 p.

Lee, P.R. 1988. Virginius Island Trail. Harpers Ferry Historical Association, Harpers Ferry, West Virginia, 16 p.

O'Connor, J.E. and Webb, R.H. 1988. Hydraulic modeling for paleoflood analysis. In, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., "Flood geomorphology," Wiley, New York, 393-402.

Partridge, J., and Baker, V.R. 1987. Paleoflood hydrology of the Salt River, Arizona. Earth Surface Processes and Landforms 12: 109-125.

Patton, P.C. 1987. Measuring the rivers of the past: A history of fluvial paleohydrology. In, E.R. Landa and S. Ince, eds., "The history of hydrology. History of Geophysics," v. 3, The American Geophysical Union, 55-64.

Patton, P.C., Baker, V.R., and Kochel, R.C. 1979. Slackwater deposits: A geomorphic technique for the interpretation of fluvial paleohydrology. In, D.D. Rhodes and G.P. Williams, eds., "Adjustments of the Fluvial System," Dendall-Hunt Publishing Co., Dubuque, Iowa, 225-252.

Phipps, R.L. 1985. Collecting, preparing, crossdating, and measuring tree increment cores. U.S. Geological Survey Water-Resources Investigations Report 85-4148, 48 p.

Reed, W.B. 1990. Virginius Island field reconnaissance: hydrology and hydraulics. Internal Report, Water Resources Division, National Park Service. Ft. Collins, Colorado, 3 p.

Shearman, J.O. 1976. Computer application for step-backwater and floodway analysis. U.S. Geological Survey, Open-File Report 76-499.

Sigafoos, R.S. 1964. Botanical evidence of floods and floodplain deposition. U.S. Geological Survey Professional Paper 485-A, 1-35.

Soil Conservation Service. 1976. "WSP2 Computer Program." Technical Release No. 61. Soil Conservation Service, Washington, D.C.

Stedinger, J.R. and Cohn, T.A. 1986. Flood frequency analysis with historical and paleoflood information. Water Resource Research 22: 785-793.

Stedinger, J.R. and Cohn, T.A. 1987. Historical flood frequency data: Its value and use. In, V. Singh, ed., "Flood frequency and risk analysis," D. Reidel, Boston, 273-286.

Stedinger, J.R., Surani, R. and Baker, V.R. 1988a. Max users guide: A program for flood frequency analysis using systematic-record, historical, botanical, physical paleohydrologic and regional hydrologic information using maximum-likelihood techniques. Department of Environmental Engineering, Cornell University, Ithaca, New York, 51 p.

Stedinger, J.R., Therivel, R. and Baker, V. 1988b. The use and value of historical and paleoflood information in flood frequency analysis: 8th Annual USCOLD Lecture, January 11-15, 1988 Meeting, U.S. Committee on Large Dams, Phoenix, Arizona.

United States Water Resources Council Hydrology Committee (USWRC). 1982. Guidelines for determining flood flow frequency. Bull. 17B (revised), U.S. Gov. Print. Off., Washington D.C.

Waitt, R.B. 1980. About forty last-glacial Lake Missoula jokulhlaups through southern Washington. Journal of Geology 88: 653-679.

Waitt, R.B. 1984. Periodic jokulhlaups from pleistocene glacial Lake Missoula-new evidence from varved sediment in northern Idaho and Washington. Quaternary Research 22: 46-58.

Waitt, R.B. 1985. Case for periodic, colossal jokulhlaups from Pleistocene glacial Lake Missoula. Geological Society of America Bulletin 96: 1271-1286.

Webb, R.H. and Rathburn, S.L. 1988. Paleoflood hydrologic research in the southwestern United States. Transportation Research Board, 67th Annual Meeting, Washington, D.C. Paper 20: 32 p.

Williams, G.P. 1988. Paleofluvial estimates from dimension of former channels and meanders. In, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., "Flood geomorphology," Wiley, New York, 321-334.

Wohl, E.E. and Enzel, Y. in press. Data for paleohydrology - availability, requirements, data bases and other global research programmes. In, "Global Continental Paleohydrology," Wiley.

Yanosky, T.M. 1982a. Effects of flooding upon woody vegetation along parts of the Potomac River floodplain. U.S. Geological Survey Professional Paper 1206, 1-21.

Yanosky, T.M. 1982b. Hydrologic inferences from ring widths of flood-damaged trees, Potomac River, Maryland. Environmental Geology 4: 43-52.

Yanosky, T.M. 1983. Evidence of floods on the Potomac River from anatomical abnormalities in the wood of flood-plain trees. U.S. Geological Survey Professional Paper 1296, 1-42.

Yanosky, T.M. 1984. Documentation of high summer flows on the Potomac River from the wood anatomy of ash trees. Water Resources Bulletin 20: 241-250.

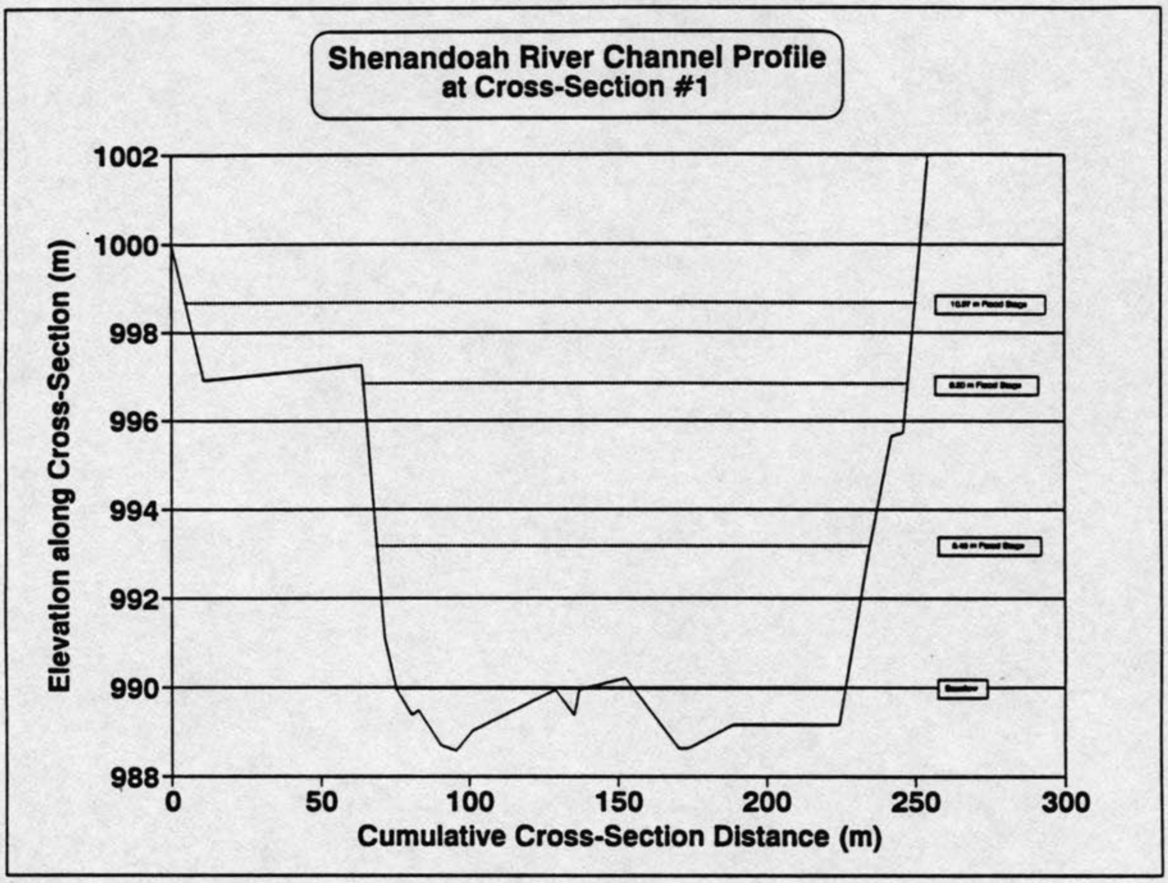
APPENDICES

Appendix 1. Systematic record for the Shenandoah River, at Millville, from 1896 to 1988.

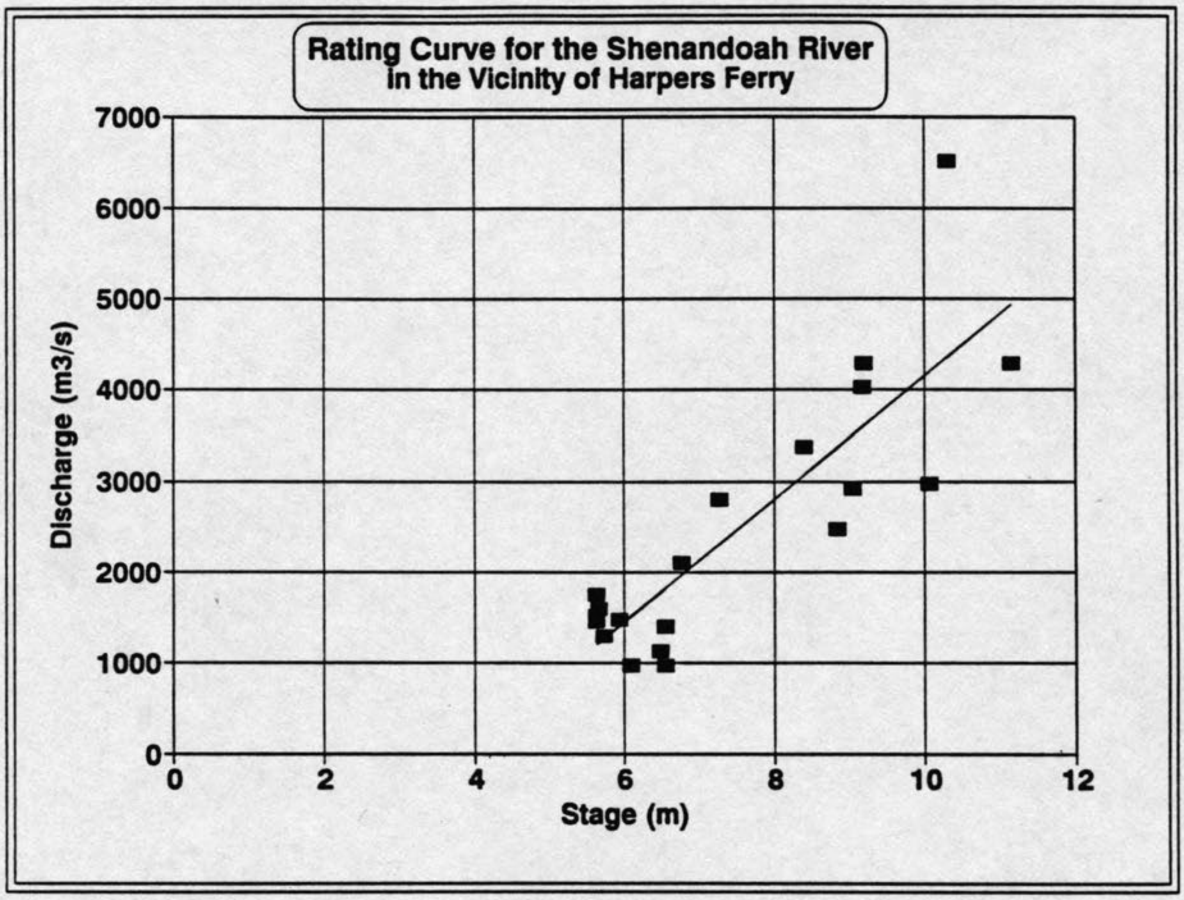
[illegible]

Cal. Yr Annual Max.	Water Yr	Discharge (ft3/s)	(m3/s)	Stage (ft)	(m)
??/??/1870	1870	151000	4273	26.4	8.0
01/25/1896	1896	16900	478	6.6	2.0
10/01/1896	1897	105000	2972	19.7	6.0
08/11/1898	1898	52000	1472	13.0	4.0
03/03/1900	1900	19200	543	7.0	2.1
04/22/1901	1901	74000	2094	16.0	4.9
01/04/1903	1903	39100	1107	11.0	3.4
07/11/1904	1904	14200	402	6.0	1.8
06/25/1905	1905	16500	467	6.5	2.0
08/28/1906	1906	14700	416	6.1	1.9
10/20/1906	1907	52000	1472	13.0	4.0
01/13/1908	1908	51300	1452	12.9	3.9
05/13/1924	1924	119000	3368	21.1	6.4
04/17/1929	1929	39900	1129	13.7	4.2
10/24/1929	1930	22000	623	10.3	3.1
08/24/1931	1931	7710	218	6.1	1.8
05/13/1932	1932	34400	974	12.7	3.9
04/21/1933	1933	39900	1129	13.7	4.2
09/18/1934	1934	12300	348	7.6	2.3
12/02/1934	1935	64800	1834	17.4	5.3
03/18/1936	1936	151000	4273	26.4	8.0
04/27/1937	1937	87400	2473	20.2	6.2
10/29/1937	1938	34400	974	12.7	3.9
02/05/1939	1939	31800	900	12.2	3.7
08/18/1940	1940	40100	1135	13.7	4.2
04/07/1941	1941	18000	509	9.2	2.8
05/24/1942	1942	56100	1588	16.3	5.0
10/16/1942	1943	230000	6509	32.4	9.9
05/08/1944	1944	21400	606	10.1	3.1
09/20/1945	1945	61800	1749	17.1	5.2
05/06/1946	1946	13200	374	7.9	2.4
03/16/1947	1947	16400	464	8.8	2.7
02/16/1948	1948	26000	736	11.1	3.4
06/20/1949	1949	53400	1511	15.9	4.9
02/03/1950	1950	16300	461	8.8	2.7
12/05/1950	1951	45700	1293	14.7	4.5
04/29/1952	1952	42900	1214	14.2	4.3
03/27/1953	1953	38300	1084	13.4	4.1
03/03/1954	1954	31200	883	12.1	3.7
08/19/1955	1955	99000	2802	21.5	6.5
03/16/1956	1956	9030	256	6.6	2.0
04/07/1957	1957	25500	722	11.0	3.4
04/28/1958	1958	19000	538	9.5	2.9
06/04/1959	1959	29800	843	11.9	3.6
05/10/1960	1960	37900	1073	13.4	4.1
04/14/1961	1961	27000	764	11.3	3.4
03/23/1962	1962	29200	826	11.8	3.6
03/21/1963	1963	35300	999	12.9	3.9
03/05/1964	1964	21400	606	10.1	3.1
02/09/1965	1965	22100	625	10.3	3.1
02/15/1966	1966	12100	342	7.6	2.3
03/09/1967	1967	40000	1132	?	0.0
03/18/1968	1968	18100	512	9.3	2.8
08/22/1969	1969	14800	419	8.4	2.5
01/02/1970	1970	17400	492	9.1	2.8
06/01/1971	1971	61300	1735	17.0	5.2
06/23/1972	1972	103000	2915	21.9	6.7
10/07/1972	1973	86200	2439	20.0	6.1
12/28/1973	1974	46200	1307	14.8	4.5
10/14/1974	1975	75900	2148	18.9	5.7
01/02/1976	1976	33400	945	12.5	3.8
10/11/1976	1977	49400	1398	15.3	4.7
01/26/1978	1978	48000	1358	15.1	4.6
02/26/1979	1979	54200	1534	16.0	4.9
10/06/1979	1980	27400	775	11.4	3.5
06/05/1981	1981	5440	154	5.0	1.5
06/15/1982	1982	29400	832	11.8	3.6
03/20/1983	1983	35700	1010	13.0	3.9
02/15/1984	1984	58600	1658	16.7	5.1
02/13/1985	1985	24700	699	10.8	3.3
11/06/1985	1986	142000	4019	25.6	7.8
05/07/1988	1988	22900	648	10.4	3.2

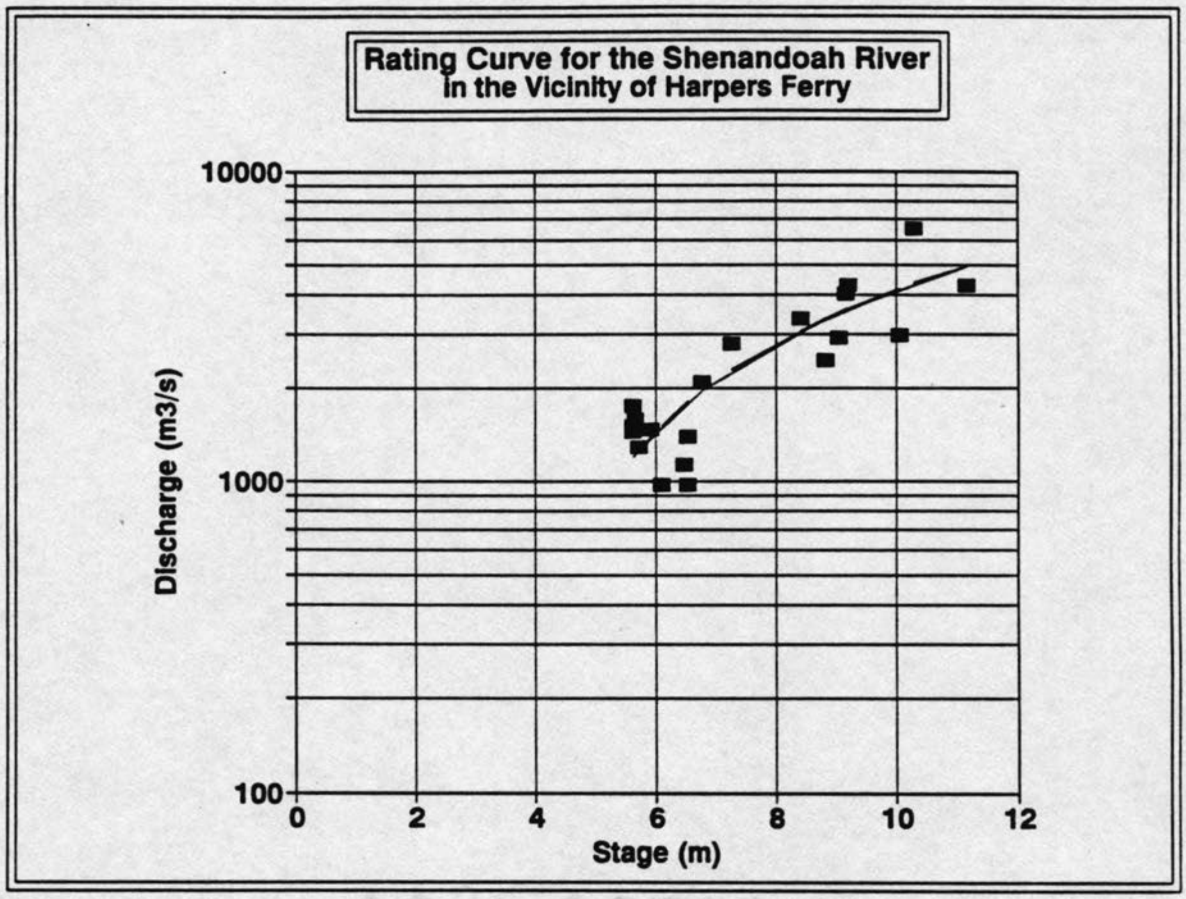
Appendix 2. Graphical representation of width and depth determination for the Manning's equation.



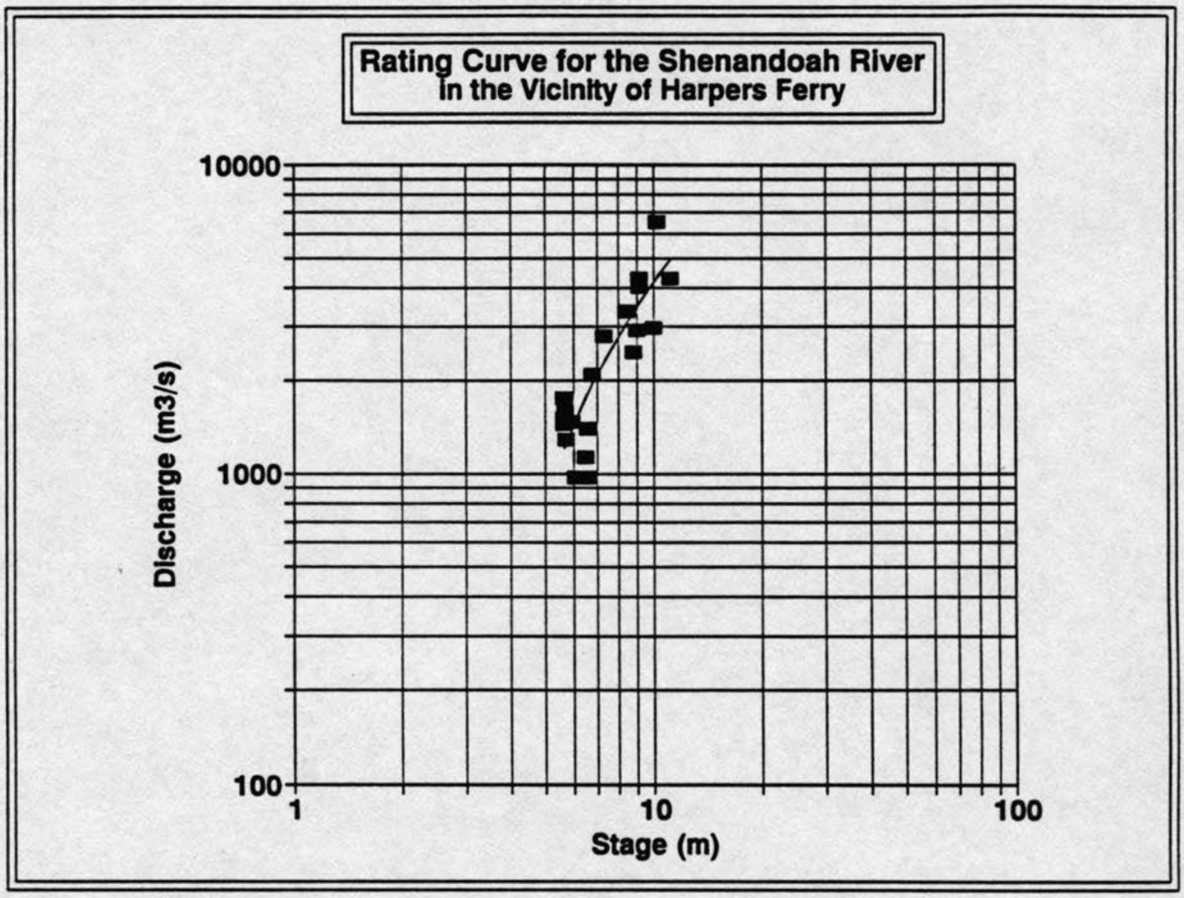
Appendix 3. Rating Curves



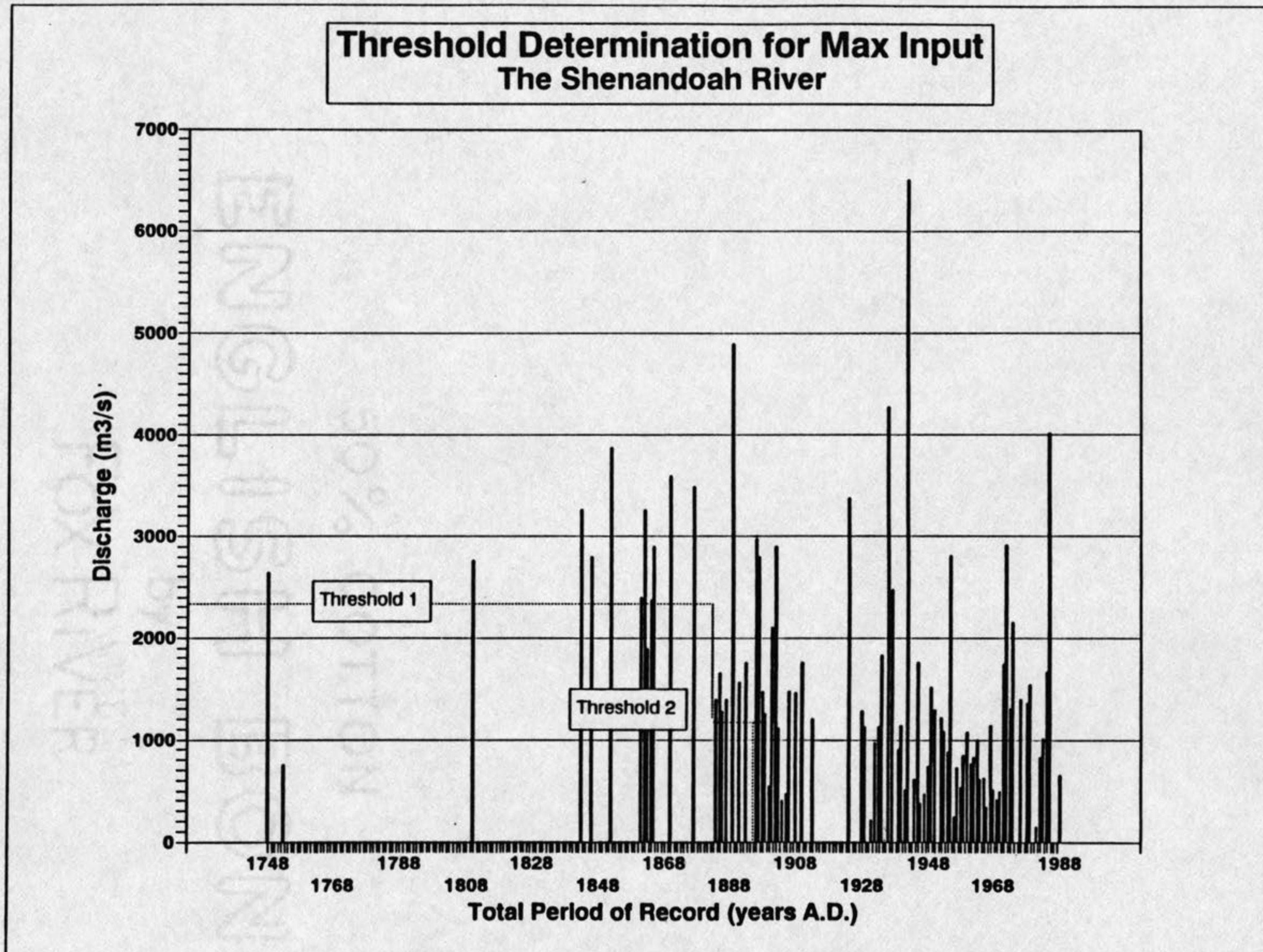
Rating curve generated from non-transformed data.



Rating curve generated from a log-normal data distribution.



Rating curve generated from a log-log data distribution.



Appendix 4. Graphical display of thresholds determined for the flood frequency analysis conducted for the entire period of record.